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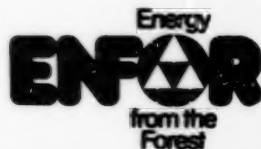
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The Role of Chemical Fertilizers in Intensive Forestry

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THE ROLE OF CHEMICAL FERTILIZERS IN INTENSIVE FORESTRY

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PREFACE

In April, 1978, a number of countries within the International Energy Agency (IEA) decided to sign an Implementing Agreement (IA) for a program of research, development and demonstration on forestry energy. The work is implemented via Programme Groups and Cooperative Projects.

Work within the group for biomass growth and production has resulted in many reports which are being published in this series. The funds for the publication of these reports have been supplied by the Biomass Energy Project of the National Research Council of Canada, the Ontario Ministry of Natural Resources, and the Canadian Forestry Service.

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ABSTRACT

This paper is aimed at giving insight into the efficient use of chemical fertilizers in forestry. The approach followed involves maintaining a broad perspective while examining those factors which play a major role in determining how fertilizers are used. Such factors have been discussed elsewhere, but the information tends to be scattered or presented within a limited framework.

Forest management is becoming more intensive and this trend is expected to continue as the demand for wood for energy and more conventional wood products continues to increase. There is an urgent need to develop ways of increasing fibre yields without harming the productivity of forest soils.

Information is presented here on the mineral requirements of higher plants. The influence of forestry on nutrient availability, fertilizer types and their application, and limitations on fertilizer use are also discussed. These discussions provide a background to the section on 'principles' of efficient use of fertilizers. Hopefully, the principles given will serve as a guide to forest managers interested in using chemical fertilizers. Future research needs related to forest fertilization are also described.

RÉSUMÉ

La communication a pour objet d'informer sur le bon usage des fertilisants chimiques en foresterie. Tout en tenant compte d'une perspective générale, elle examine les principaux facteurs des modalités d'utilisation des fertilisants. Ces facteurs ont été discutés ailleurs, mais l'information tend à être dissimulée ou à être présentée dans un cadre limité.

L'aménagement forestier tend à s'intensifier et cette tendance devrait se maintenir à mesure que la demande de bois, pour en tirer de l'énergie et davantage de produits classiques, continue à augmenter. Il est urgent de trouver des moyens d'accroître le rendement en cellulose sans porter atteinte à la productivité des sols forestiers.

L'information présentée porte sur les besoins minéraux des plantes supérieures. L'influence de la foresterie sur la disponibilité des éléments nutritifs, les types de fertilisants et leur utilisation ainsi que les limites de la fertilisation font aussi l'objet d'une discussion. Celle-ci sert d'introduction aux principes du bon usage des fertilisants. Il est à souhaiter que ces principes sauront guider les aménagistes. Les besoins de la recherche à venir sont aussi décrits.

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INTRODUCTION

The aim of this paper is to examine the topic of forest fertilization with the goal of more efficient fertilizer use in mind. Information on the subject is often scattered or presented within a limited framework. This paper attempts to compile and interpret some of the large quantity of information available on the topic. Particular importance is placed on the description of fertilizer types, consideration of the role of fertilizers within intensive management systems and on discussion of some of the principles involved in the efficient use of fertilizers. Hopefully, the paper will assist in promoting greater understanding of chemical fertilizers and their application in forestry, and stimulate further thought and activity on their use.

Forest fertilization is not widely practiced in the world today. World forests cover approximately 2.8 million hectares or 22% of the earth's land area (Persson, 1979). Probably only 0.20% to 0.25% of this forested area has received any form of fertilizer (Baule, 1973). This represents an area smaller than 10% of the world's plantation forests which cover an estimated 100 million hectares.

Many forest soils are of low fertility and intensive management places greater demands on these soils. Furthermore, nutritional problems are more likely to develop in plantation forests. World expansion of managed forest plantations has resulted in a parallel increase in soil fertility problems (Pritchett, 1979).

A positive growth response to fertilization does not necessarily mean that all is well. The resulting yield increase must be weighed against fertilization costs, including any adverse effects of adding fertilizers on site productivity. The scenario puts greater responsibility on foresters to plan fertilization programs in terms of both tree and soil management.

BACKGROUND

Intensity of management affects nutrient availability. The trend in forestry today is towards more intensive management. This covers a range of management possibilities. Intensive harvesting, for example, has been used to describe nearly the full range of harvest rates and cultural inputs (Stone, 1979). Intensive forest management is similarly not clearly defined. Nevertheless, they both generally refer to the use of shorter rotations, closer utilization and more intensive culture.

Further intensification of forest management is likely in the future as timber supplies decline and the demand for wood rises. Expected increases in forest biomass use for energy will add to the high wood demand for other forest products. Meanwhile, the forest land base is shrinking in response to environmental, conservation, recreation, water regulation and scientific needs (Carlisle, 1980). Forest managers are faced with the task of supplying more wood from a smaller land area. This places greater pressures on forest soils.

Forest fertilization implies more than just maintaining soil nutrient levels. Overall site productivity needs to be conserved, including soil organic matter, ion exchange capacity, soil pH and soil form, but an excess of mobile ions in the soil profile can result in high nutrient losses and inefficient fertilizer use. An over-supply of one nutrient can result in other nutrient deficiencies.

Chemical fertilization is only one facet of forest management. Other ways of maintaining site quality are available. Less energy-demanding biological methods of soil amelioration may be more suitable in many instances. Harvest operations can be modified to reduce impacts on site productivity. Prompt replanting of clear-cut areas helps to stabilize soils and maintain nutrients released following harvesting. An efficient fertilization program needs to consider such alternatives in the planning stages and coordinate them with other management activities.

Establishing an efficient fertilization program is not easy. Nutrient deficiencies must first be accurately identified. The best fertilizer type or combination should then be selected and properly applied. The timing and rate of fertilizer application are both extremely important. They should reflect specific species and site nutrient requirements. Heavy nutrient losses associated with fertilizer use need to be minimized, while optimal fibre yields are produced.

This paper will describe factors which affect the efficient use of chemical fertilizers in forestry, beginning with a basic discussion on plant nutrient requirements. Later sections will examine the influence of intensive forestry on nutrient availability, fertilizer types and their application, fertilizer use in conventional forestry and limitations on fertilizer use in intensive forest management. These earlier sections will hopefully help provide insight into the work on 'principles' of efficient fertilizer use and 'research needs' which follow.

PLANT NUTRIENT REQUIREMENTS

Most elements listed in the periodic tables have been isolated from plant material, but only sixteen elements are generally required by higher plants. The elements used in relatively large quantities by plants are carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S). They are referred to as macronutrients. Carbon, hydrogen and oxygen are supplied by air and water. Consequently, they are not considered as nutrients by the fertilizer industry. The elements needed in smaller quantities, called micronutrients or trace elements, are boron (B), chlorine (Cl), copper (Co), zinc (Zn), iron (Fe), manganese (Mn), and molybdenum (Mo). Some plants have become adapted to require slightly fewer or additional elements. An element is considered essential if it meets either one of two criteria, namely (1) if the plant is not able to complete its life cycle without it, or (2) if it makes up part of the molecule of an essential plant constituent or metabolite (Epstein, 1972).

Each essential element has an important role to play in plant development. However, the relative amount of each element required varies considerably (Table 1).

Table 1: Estimated Nutrient Weight Proportion (N = 100) in Seedlings Growing at Maximum Growth Rates

Nutrients	Species		
	<u>Pinus sylvestris</u>	<u>Picea abies</u>	<u>Betula verrucosa</u>
Nitrogen (N)	100	100	100
Potassium (K)	45	50	65
Phosphorus (P)	14	16	13
Sulphur (S)	9	9	9
Calcium (Ca)	6	5	7
Magnesium (Mg)	6	5	8.5
Iron (Fe)	0.7	0.7	0.7
Manganese (Mn)	0.4	0.4	0.4
Boron (B)	0.2	0.2	0.2
Copper (Cu)	0.03	0.03	0.03
Zinc (Zn)	0.03	0.03	0.03
Chlorine (Cl)	0.03	0.03	0.03
Molybdenum (Mo)	0.007	0.007	0.007

(from: Ingestad, 1979)

Whether or not an element is limiting to growth is dependent on many factors including the demands of individual species, inherent site fertility, climatic conditions and the level of management maintained. The uptake and function of each nutrient element is briefly described as follows:

Nitrogen

Nitrogen is the soil nutrient required in greatest quantity by plants. Most soil nitrogen is found in organic materials on the forest floor and as such, is largely unavailable for uptake by higher plants. Organic nitrogen is gradually transformed by microorganisms during decomposition to the inorganic state either as ammonium (NH_4^+) or nitrate (NO_3^-) ions, through the process of mineralization (Alexander, 1977). Plants utilize both nitrate or ammonium, but the availability of these ions in the soil is determined largely by the rate of mineralization. Plant species often show preferences for nitrogen in either the ammonium or nitrate form. This preference may vary with soil pH. Populus spp., for example, can be indifferent to the form of nitrogen while growing on alkaline soils, but prefer nitrate on acid soils (Bonneau, 1973). Nitrate is the more mobile form of available nitrogen. It is easily lost from the soil profile.

Nitrogen in its reduced state is an essential component of amino acids (building blocks of proteins and enzymes), nucleotides, porphyrins, alkaloids, and some lipids. Nitrate taken up by plants is rapidly reduced to ammonium through an enzyme containing molybdenum. The reduced nitrogen, together with some carbohydrates, is converted to amino acids, mainly in the leaves.

Phosphorus

Phosphorus plays a major function in the accumulation and release of energy during cellular metabolism. Phosphorus is an important component

of phospholipids, nucleoproteins and phytin. Soils vary considerably in their ratio of organic to inorganic phosphate. Inorganic phosphorus is usually found in the form of complex calcium phosphates, such as fluorapatite, chlorapatite, apatite, vivianite and goethite in alkaline soils and as hydroxy phosphate of aluminum and iron in acid soils. These insoluble inorganic compounds are largely unavailable to plants. However, many microorganisms, mainly through the production of organic acids, assist in weathering these minerals and help to bring phosphate into solution. Microorganisms are also responsible for the mineralization of organic phosphates. Large quantities of organic phosphate enter the soil during plant litter decomposition, and, like organic nitrogen, is mainly unavailable to higher plants until its conversion to an inorganic form.

Phosphorus is absorbed by plants mainly as two phosphate anions. The ions involved are the primary orthophosphate anion ($\text{H}_2\text{P}_2\text{O}_7^{4-}$) and the secondary orthophosphate anion (HPO_4^{2-}). The availability of these ions depends directly on soil pH. HPO_4^{2-} is the major form found in solution in alkaline soils. Slightly to moderately acid soils are favourable for the presence of both anions, while in very acid soils available phosphorus is largely found as H_2PO_4^- . The amount of phosphorus in the soil solution which is available to plants at any one time is normally very small (never larger than a few tenths of a part per million) relative to the amount of total soil phosphorus (Pollett *et al.*, 1981). It is necessary for plant growth that this supply be continually renewed.

Potassium

Potassium is utilized by higher plants in larger amounts than any other mineral element except nitrogen and, in some situations, calcium. It is not known to enter into the structure of organic materials. Potassium is commonly found as a structural element in a variety of rocks and minerals, particularly in feldspars and micas. This so-called "fixed" potassium is only moderately available to plants. The readily available potassium cation (K^+) is either held by the soil colloids or located in the soil solution. In acid soils which contain considerable amounts of exchangeable aluminum (Al^{3+}) and in soils containing montmorillonite, vermiculite, and illite, the aluminum ions displace the absorbed potassium on exchange sites. In such circumstances, potassium can limit growth.

Potassium is unique in being the only major element without a molecular form in living organisms. Instead, it remains in ionic form within the tissues of higher plants. Consequently, it is easily leached from plant foliage. Potassium is essential to all metabolic processes within the cell. It influences the uptake of other nutrient elements, the activity of enzymes, and acts as a regulator of certain processes including the rates of respiration and transpiration. Potassium is also involved in the production and translocation of carbohydrates.

Calcium

Calcium is needed by plants in amounts greater than any of the other secondary nutrients. It also plays an important role in correcting soil structure. Calcium is quite abundant in most soils, and occurs in such minerals as feldspars, amphibole, pyroxene, dolomite, calcite, apatite and gypsum. Calcium levels in soils range from 0.5% in sandy soils to over 5%

in some soils, such as those developed from limestone. The calcium ion (Ca^{2+}) is readily taken up from the soil solution by plants. Like potassium, if it is adsorbed on the surface of soil colloids it is considered to be exchangeable and, therefore, available to higher plants.

Calcium is often the major cation on soil particles because of its abundance and because it is held more tightly than either magnesium or potassium ions. Calcium, therefore, is not readily leached. Its presence improves soil structure, raises pH levels and assists the aggregation of colloidal clay and humus particles, making the soil more granular. This improves water and air penetration into the soil.

Calcium is found in every plant cell. It is essential for normal cell elongation, protein formation and cell division (mitosis). In stems and leaves, calcium frequently occurs as calcium pectates which are deposited in and along cell walls, providing thickness and strength. Calcium is relatively immobile within the plant, and is not easily redistributed in a plant under stress. Consequently, plants require a continuous supply of calcium.

Magnesium

Magnesium is a major element in chlorophyll which makes it essential for photosynthesis. Chlorophyll-a, for example, has the formula $\text{C}_{55}\text{H}_{72}\text{O}_5\text{N}_4\text{Mg}$. Magnesium is also involved in the production of many plant compounds including sugars, proteins, oils and fats. It affects the uptake of other plant nutrients, particularly phosphorus, and plays a role in the translocation and metabolism of carbohydrates. Magnesium is also responsible for activating a number of key enzymes.

Magnesium is a positively charged cation (Mg^{2+}) which is held by the negatively-charged surface of clay and organic particles. Positioned on these exchange sites, it is available to plants. Magnesium is not readily leached. It is usually abundant in most soils and is found in a variety of minerals including amphibole, biotite, chlorite, dolomite, montmorillonite, olivine, pyroxene, serpentine, and vermiculite. Light-textured acidic soils and organic soils containing free calcium carbonate tend to be deficient in magnesium. High levels of potassium are known to accentuate any magnesium shortages.

Sulphur

The availability of sulphur is directly related to the level of microbial activity in the soil. Sulphur is like nitrogen in that most of it is normally found in soils in the organic form, and consequently is largely unavailable to plants. Inorganic sulphur is gradually released through mineralization when environmental conditions favour organic matter decomposition. Sulphur is generally very mobile within plants. It is absorbed mainly as the sulphate (SO_4^{--}) ion, although several amino acids containing sulphur may be assimilated without prior degradation. Sulphate is reduced within plant tissues to the sulphydryl ($-\text{SH}$) form.

Sulphur is another element which is found within every plant cell. It is involved with the synthesis of amino acids, particularly with the two sulphur-containing amino acids, cysteine and methionine, and is necessary for the formation of vitamins, enzymes and some plant hormones.

Iron

Iron occurs either in the metallic form (Fe), or as ferrous (Fe^{2+}) and ferric (Fe^{3+}) oxides. Besides its predominance as iron oxides, it is abundant in many other minerals including carbonates, micas, amphibolite and clays. Soil pH is a major factor in determining the solubility of ferric iron; the level of ferric iron in soil solution falls rapidly with increasing pH. It is very unlikely, however, that plants depend solely on ferric ions present in the soil solution (Russell, 1973).

The absorption of iron by plants varies with the capability of the plant to reduce iron from the ferric to ferrous form. This reduction is necessary before absorption can occur. Iron is practically immobile within plant tissues and does not move from old to new tissues even under stress situations. A continuous supply is needed if normal plant development is to be achieved.

Iron is necessary for many metabolic processes in plants, and is essential for the maintenance of chlorophyll. It is an important component of leghaemoglobin, a substance required for nitrogen fixation in legumes. Non-heme proteins or ferredoxins, which also contain iron, are also needed for nitrogen fixation as well as for other functions such as electron transfer in chloroplasts.

Manganese

Manganese plays a role in electron transfer during photosynthesis and is a part of two enzyme systems, arginase and phosphotransferase. It can substitute for magnesium in some enzymes needed for glycolysis (sugar metabolism). This element is also required for chlorophyll production.

Manganese has a complex soil chemistry. It occurs in a number of oxidized forms all differing in their availability to plants. Manganese ions are found in soil in both the tetravalent (Mn^{4+}) and divalent (Mn^{2+}) form. It is known that plants readily assimilate the latter however, the tetravalent manganese ion is probably not used by plants. The ion that predominates in soil is very much affected by pH; in very acidic soils (pH lower than 5.5), manganese occurs mainly as Mn^{2+} while Mn^{4+} is more common in very alkaline soils. Consequently, manganese deficiencies are usually found under alkaline conditions. In the more neutral pH range, the activity of the microflora, which have the capability of transforming manganese, is important in determining its availability.

Copper

Copper is a constituent of a number of important enzymes such as cytochrome oxidase, ascorbic acid oxidase and laccase, which are involved in the reduction of molecular oxygen to water. Copper is also found in plastocyanin, an enzyme involved in the electron transfer chain active during photosynthesis.

Copper is most often found in sulphide minerals, although it may occur in silicates, carbonates and sulphates. Within these compounds, it has two forms, either cuprous (Cu^+) or cupric (Cu^{2+}). The cupric form

(Cu^{2+}) is important in plant nutrition, and is strongly adsorbed on both mineral and organic exchange sites. The availability of copper decreases markedly as soil pH increases. Once copper is delivered within the plant, it is relatively immobile and must be continually replenished.

Zinc

Zinc is frequently an element in sulphide and silicate minerals, and always exists as a divalent cation (Zn^{2+}). Like many of the other metallic micronutrients, its availability drops as soil pH increases. Consequently, most zinc deficiencies are associated with alkaline soils.

Zinc is essential in the formation of some enzymes involved in electron transfer, including a number of dehydrogenases, proteinases, and peptidases. It is also required for protein synthesis and degradation. Its deficiency has resulted in lower levels of RNA (ribonucleic acid) and ribosome in cells.

Molybdenum

Molybdenum is the rarest of all micronutrients. It is normally found as the molybdate anion (MoO_4^{2-}), but in very acidic conditions it occurs as HMoO_4^- . The availability of molybdenum is directly opposite to the response of other micronutrient elements to changes in soil pH; increases in soil pH favour molybdenum availability.

Molybdenum is required during reduction of nitrate to nitrite, and is specifically involved with electron transport when this process is taking place. Molybdenum carries out a similar function during nitrogen fixation. It is probably also needed for other plant processes, but these have yet to be described.

Boron

Boron is the micronutrient which probably most often limits yield. Boron and chlorine are the only non-metals in the soil trace element group. Boron is always found in combination with oxygen in minerals such as tourmaline, or in other more weatherable minerals. Relatively little is known about the form of boron within these minerals. Boron exists in soil solution as boric acid (H_3BO_3) and is also found in ionic form (H_2BO_3^-) at pH levels above 9.2. Boron is probably adsorbed in one or more ionic forms, particularly by organic matter. These ions are available to plants, but because boric acid is predominate in soil solution at lower pH levels, plant uptake of the undisassociated acid is more likely to occur.

The role of boron in plant development is not well understood. It is considered important for sugar transport across cell membranes, and boron deficiencies appear to limit root growth, resulting in the accumulation of polyphenolic compounds and lowering of plant transpiration rates. Deficiencies of boron are common in sandy acid soils. Since boron is the most mobile of the micronutrients, it is readily leached in light textured soils, especially when levels of organic matter are low.

Chlorine

Chlorine is the most recent element found to be essential for plant growth. It occurs as the chloride anion (Cl^-) in soluble salts. This anion is not readily adsorbed, and is consequently used as a tracer for determining the movement of other soluble anions such as nitrate.

Little information is known about chloride deficiencies or their effect on plant metabolism. Chlorine is involved in a number of reactions within photosynthesis, particularly those reactions which are responsible for the capture and conversion of light energy into the high energy state created by the formation of phosphate bonds.

The Role of Elements in Tree Nutrition

The mineral nutrients can be generally classified by their function (Clarkson and Hanson, 1980), as shown in Table 2. Nitrogen, phosphorus and sulphur are covalently bonded with carbon, hydrogen and oxygen, giving plants the essential properties of life. The other nutrient elements are all found in inorganic salts and complexes, and interact with the biological molecules within the plant. Interactions vary from bonds which are largely ionic to those that are strongly covalent. Their properties are interconnected within an enzyme or structural complex. As a result, roles of individual elements are often difficult to determine. Many properties are not yet fully understood.

Table 2: A Functional Classification of the Essential Nutrient Elements

Covalently Bonded with C, H, O		Salts and Complexes		
Reduced	Oxidized	Molecular Structure	Oxidation- Reduction Reactions	Uncertain
N	P	K	Fe	B
		Mg	Cu	Cl
S	S	Ca	Mo	
		Mn	Mn	
		Zn		

(from: Clarkson and Hanson, 1980)

Plants require a 'balanced' nutrition for proper growth and development. Nutrient elements are needed in the right proportions if optimum growth is to be achieved. Nutrient interactions have an important influence on how this nutritional balance is maintained. Ionic antagonism can occur. For example, an increase in the supply of a particular cation may induce a deficiency of another cation (Russell, 1973). The optimal nutrient supply for a particular species is subject to change, therefore, in response to fluctuations in nutrient levels and their associated interactions. Environmental conditions i.e. light, temperature and moisture supply,, are also critical in determining a plant's nutrient needs at any given moment.

It is well recognized that different forest tree species have their own nutritional requirements (Rennie, 1955) and whether or not these are fulfilled can only be decided on a site-species specific basis. Age and growth rate are important tree characteristics which determine how much nutrient is accumulated in a stand. Soil fertility is, of course, another important factor, since plants tend to accumulate more nutrients than they really need when nutrient levels are high (Ingestad, 1974). Nutrient requirement is a physiological concept (Tamm, 1964) implying a certain growth performance for the level of nutrients supplied. From a nutritional standpoint, the ideal forest management regime would allow maximum growth with a minimum amount of nutrient elements supplied in the proper proportions.

INFLUENCES OF INTENSIVE FORESTRY ON NUTRIENT AVAILABILITY

The intensification of forest management places greater stresses on forest soils. For example, Switzer and Nelson (1973) showed a significant increase in nutrient demand in two natural stands of loblolly pine (*Pinus taeda*), which were managed on a shorter rotation and with more intensive utilization (Table 3). Both practices increased nutrient demand, but it was found that closer utilization affected demand more than the shortening of rotation length. The additional fibre, obtained by harvesting the entire above-ground tree biomass, has a higher concentration of nutrient elements than the merchantable stem (Wells and Jorgensen, 1979), adding to the magnitude of any nutrient drain associated with whole-tree harvesting. In a similar fashion, nutrient concentrations decrease as trees mature (Madgwick *et al.*, 1977). More juvenile wood, with its higher nutrient concentration, is extracted from the site when trees are harvested under shorter rotations.

Table 3: Mean Annual Nutrient Demands of Natural Loblolly Pine (*Pinus taeda*) as Affected by Shortening Rotation Length and Intensifying Tree Utilization

Nutrient	Partial Tree Utilization		Complete Tree Utilization	
	20 yr. Rotation	40 yr. Rotation	20 yr. Rotation	40 yr. Rotation
	(kg/ha/yr)			
N	14.6	11.6	19.2	14.2
P	0.84	0.69	1.35	1.01
K	8.4	7.3	10.6	8.6
Ca	8.9	7.6	10.2	8.7

(from: Switzer and Nelson, 1973)

Apart from nutrient losses associated with actual wood removal, forest harvesting can also increase losses from volatilization, leaching

and erosion. Harvesting allows additional light, heat and moisture to reach the forest floor and, consequently, decomposition activity is usually increased. These conditions can accelerate losses of nitrogen by denitrification, leaching of ions beyond the rooting zone (e.g. Ca, Mg, K, NO₃) and soil erosion (McColl and Grigal, 1979). The more frequent harvests involved in managing forests intensively will increase nutrient losses caused by such mechanisms.

Making good predictions on the effect of intensive forestry on nutrient availability is not easy. While it is simple to demonstrate and increased demand for nutrients in stands under intensive management, it is difficult to determine the intensity of management at which site fertility is being seriously eroded. Earlier approaches to predicting nutrient needs by producing nutrient inventories, as summarized by Rennie (1955), or by making crude nutrient budgets, are not satisfactory. Nutrient budgets provide valuable information on nutrient inputs via precipitation, aerosols, dusts, adsorption of gases from the air and biological nitrogen-fixation (Miller, 1979), and also include estimates of nutrient losses. However, these are a typical 'black box' approach giving inputs and outputs but providing little information about processes or site impacts.

In attempting to understand the overall consequences of intensive forestry on soil fertility, computer simulation techniques have proved to be very useful (Aber et al., 1978; Kimmins et al., 1980). Computer models give ecologists an opportunity to examine the three interrelated levels of nutrient cycling simultaneously. The geochemical cycle, the movement of nutrients between soils and plants, and the biochemical cycling within plants themselves, can all be incorporated into a single model.

As noted by Kimmins (1982), if we are going to answer the question of the long-term consequences of intensive forestry on soil fertility, answers are required to the following questions:

1. What percentage of the nutrient capital is removed by harvesting?
2. What is the effect of reducing the rotation length?
3. How large are other harvest-induced losses? e.g. denitrification
4. How available are the remaining nutrients?
5. How rapidly are losses replaced?
6. What are the nutrient requirements of the next crop?
7. How important are nutrients in regulating the production of crop species?
8. What are the ecological and economic possibilities of replacing harvest-induced losses?

The above questions, most of which involve improved nutrient budgeting, will not likely be fully answered for many years, but two features of Kimmins's (1982) approach to examining consequences of

intensive forestry are applicable to a discussion on fertilization. First of all, while it may be impossible to obtain exact answers concerning the consequences of management activities on nutrient availability, it is possible to examine trends. Secondly, one cannot explain a complex factor by working with a single variable. Computer simulation enables the researcher to vary numerous interrelated variables simultaneously and study ecosystem response. While all models are limited in that they are only simulating reality, they do provide insight into the complex relationships involved.

FERTILIZER TYPES AND APPLICATION METHODS

Ever since man has cultivated crops, he has added fertilizers to increase crop yields. Some examples of the first fertilizers utilized are animal manures, bones, wood ashes, wool wastes, guano, fish, chalk and marl. Early accounts of fertilizer use provide interesting insights into the origin and development of commercial fertilizers (Hall, 1948; Collings, 1949). A relatively short list, compared to today's standards, was constructed by Collings (1949) showing nitrogen, phosphorus and potassium fertilizer materials manufactured in the year 1900 (Table 4). The extensive use of fertilizer materials has occurred quite recently, as new chemical fertilizers have been developed and marketed.

Table 4: NPK Fertilizers Manufactured in 1900

Nitrogen Sources		Phosphoric Acid Sources	Potash Sources
Inorganic	Organic		
Ammonium sulphate	Castor pomace	Basic slag	Kainite
Sodium nitrate	Cottonseed meal	Precipitated phosphate	Manure salts
	Dried blood	Superphosphate	Potassium chloride
	Fish scrap	(then called acid phosphate)	Potassium sulphate
	Rough ammoniates		Sulphate of potash-magnesia
	Tankage		

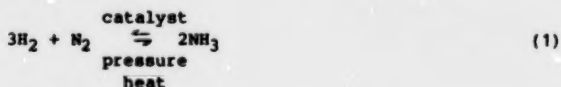
(from: Collings, 1949)

"Chemical" fertilizers are manufactured products which contain nutrient elements in relatively available forms. This distinguishes them from organic fertilizers derived from plant and animal remains. The first use of chemical nitrogen fertilizers was probably in 1665 when Sir Kenelm Digby increased crop yields by applying saltpeter. None of the associated principles involved were known until 1804 when Nicholas Theodore de Saussure of Switzerland wrote about the uptake by plants of ash ingredients and indicated that they were essential for plant growth. Fifty years later, a German chemist, Justus von Liebig, developed his now famous theory of plant nutrition and described how carbon compounds are derived from the atmosphere. He suggested that if a plant is supplied with about 2% of its dry weight as mineral elements, the plant is

nutritionally capable of proper growth. The essential role of nitrogen was not recognized until 1957 when Laws, Gilbert and Pugh, at Rothamsted Experiment Station in England, established the fact by a series of experiments. A description of the major fertilizer types used today, beginning with nitrogen fertilizers, is given below.

Nitrogen Fertilizers

Most nitrogen fertilizers today are produced synthetically from anhydrous ammonia (NH_3). Production on a commercial scale was not possible until 1908 when two German chemists, Fritz Haber and Carl Bosch, discovered a practical method of combining nitrogen and hydrogen. The reaction involved in the process is known as the Haber-Bosch reaction. It can be simply written as:



The resulting ammonia gas is essentially free of water and contains approximately 82% nitrogen.

Ammonia

Ammonia may be used directly as a fertilizer or it can be converted to ammonium salts, nitrates or urea. The main advantage of applying anhydrous ammonia directly is its low cost. Wherever ammonia can be applied as is, it is the least expensive source of nitrogen. The direct application of ammonia amounts to 37% of all nitrogen fertilizer applied in the United States. It is also very popular in Denmark and several other European countries (Hignett, 1974).

Greater use of anhydrous ammonia is somewhat restricted by difficulties associated with its storage, transportation and application. Such problems are related directly to the specific properties which are characteristic of ammonia. Ammonia must be cooled before storage, for example, to a temperature of -33°C at the atmospheric pressure at sea level. Storage tanks have been designed and constructed to maintain this constant temperature, even during transport. Ammonia is transported between storage terminals either by ship, barge, rail, pipeline or truck. When ammonia is moved by pipeline between terminals, it must be warmed to at least 2°C or the pipes develop brittle fractures. The ammonia must be recooled following transport. The best method of transportation varies with the particular circumstances and locations involved. The choice of transportation has a considerable effect on fertilizer costs (Hignett, 1979).

Anhydrous ammonia is applied as a liquid with a high vapour pressure. Therefore, it must be injected 15 to 25 cm below the soil surface to prevent large gaseous losses. The injection is normally carried out using applicators with special knives which form the slits in the soil into which the ammonia is fed. Applicators are available in a range of sizes from a small five-row size to equipment having swath widths up to twenty metres. In an attempt to lower application costs, the tendency is towards the use of larger applicators, or as an alternative, applying the ammonia during other tilling operations (IFDC, 1979).

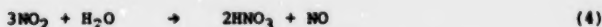
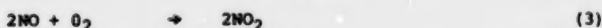
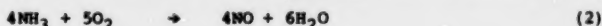
While ammonia has been mainly used for agriculture, considerable effort has gone into testing the response of applying anhydrous ammonia to forest soils in Germany (Bengston, 1973). Growth responses were not as good for ammonia application as for similar rates of nitrogen applied as salts. This discrepancy is probably a result of losses of gaseous ammonia from the injection slits. These losses could probably be reduced by improving application techniques.

Anhydrous ammonia has many advantages which may make it useful under some situations in intensive forestry. A range of agricultural equipment is already available which could be tested for application of ammonia under forestry conditions. While most of this equipment is designed for gentle terrain and soils free of obstructions, it may be easily adapted to intensively-managed, better-quality forestry sites. Ammonia is relatively easy to apply. It can be placed within the soil at the desired depth and is the most economical form of nitrogen fertilizer available.

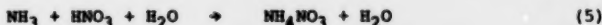
Ammonium Nitrate

Ammonium nitrate (NH_4NO_3) is the most popular form of nitrogen fertilizer in most European countries, and its use is widespread throughout the world. Ammonium nitrate is often more readily available to crops than other types of nitrogen fertilizers. Many crops prefer nitrate and, consequently, ammoniacal nitrogen must be nitrified in the soil before it becomes effective. The nitrification process is normally rapid in warm soils, but slow in cool soils at temperatures of 10°C or below (IPDC, 1979).

Ammonium nitrate is manufactured by oxidizing ammonia to nitric acid (HNO_3) and then neutralizing the nitric acid by adding more ammonia. The basic chemistry involved in the production of the nitric acid, referred to as the Ostwald process, consists of the following reactions:



Nitric acid is concentrated and then the ammonia is added to produce an aqueous solution of ammonium nitrate:



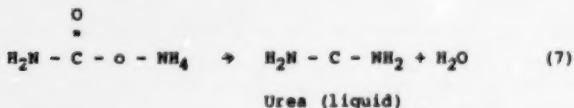
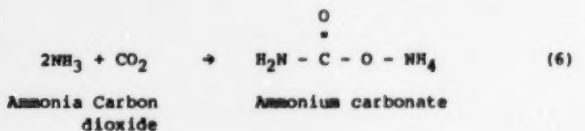
The ammonium nitrate solution can be used directly for the production of other nitrogen solutions. If solid ammonium nitrate is being made, the solution is concentrated and later converted to a solid within a prilling tower or a rotary drum granulator (Follett *et al.*, 1981). The prills or particles are then further dried, coated, screened and stored. Coating with a diatomaceous earth resists water and prevents the ammonium nitrate particles from caking, which can lead to severe handling problems.

Ammonium nitrate has some disadvantages which have led to a decline in its usage over the last several years. Its high affinity for water has made it necessary to air-condition warehouses where it is stored to lower

the humidity and reduce caking. Unless used with suitable precautions, ammonium nitrate presents risks of fire or even explosions. It is not as effective as some other nitrogen fertilizers on flooded areas. The production of ammonium nitrate is subject to severe environmental restraints because of the possibility of high nitrous oxide emissions (NO and NO_2) to the atmosphere and also because of dust produced during the prilling and coating process. Future use of ammonium nitrate is likely to decline, but it will continue to be manufactured as an important component of nitrogen solutions.

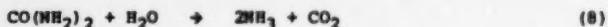
Urea

On a world scale, urea ($\text{CO}(\text{NH}_2)_2$) is presently the most popular and most concentrated solid nitrogen fertilizer; it is 46% nitrogen. Urea is widely used particularly in Asia where approximately 85% of the nitrogen fertilizer industry is designed for urea production. Urea is produced from anhydrous ammonia and carbon dioxide at high temperature and pressure. The carbon dioxide is a by-product of ammonia production resulting from carbon compounds in natural gas. In the synthesis of urea, ammonia and carbon dioxide react to form ammonium carbonate. The ammonium carbonate decomposes into ammonia and urea. The ammonia is recycled while urea is drawn off as a liquid. The reactions involved are:



The liquid urea is then concentrated to a high level, sufficient for the production of solid urea. The concentration process is critical because if it is done at excessively high temperatures, a compound called biuret is formed from two molecules of urea. Biuret is toxic to many plants and occurred in relatively high concentrations in some of the first solid urea produced. Once the urea solution is concentrated, it is treated similarly to ammonium nitrate to produce pills or liquids.

The use of urea as a fertilizer was hindered, at first, because of production difficulties and doubts about its effectiveness. It was generally considered to be a slow-release fertilizer under European conditions, because it goes through two transformations before it becomes available to most crops. Applied urea is first transformed by hydrolysis:

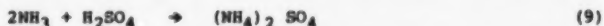


The ammonia is then transformed through the nitrification process to nitrate. These reactions proceed rapidly in warm, moist soils but are carried out more slowly in the cooler soils characteristic of areas having more temperate climates.

Urea is preferable to nitrates for use in flooded areas, such as rice fields, because nitrates are reduced by denitrification to nitrous oxide (N_2O) or nitrogen gas under anaerobic conditions, which can lead to substantial nitrogen losses. For this reason, together with its high nitrogen concentration and relatively low production costs, urea is now the most popular nitrogen fertilizer form in Asia and in many countries on other continents.

Ammonium Sulphate

Ammonium sulphate $[(NH_4)_2 SO_4]$ was at one time the leading form of nitrogen fertilizer. It is manufactured as a by-product from a number of industrial processes. Ammonium sulphate is produced simply by combining sulphuric acid with ammonia. The reaction is:



Ammonium sulphate is characterized by having a low hygroscopicity, good physical properties, and chemical stability. It is an effective fertilizer, providing both nitrogen and sulphur. The latter element is beneficial on alkaline soils or for some crops such as tea, but for many situations sulphur can be a disadvantage. Another problem with ammonium sulphate is its low nitrogen content (21%) which results in higher costs for packaging, storage and transportation. Consequently, urea and ammonium nitrate are often more economical than ammonium sulphate.

Sodium Nitrate

Before the use of synthetic ammonia and its derivatives, sodium nitrate ($NaNO_3$) was an important nitrogen fertilizer in many countries. It originates mostly from a large natural ore body located in eastern Chile. Sodium nitrate can also be manufactured synthetically from nitric acid and sodium carbonate. Like all nitrates, sodium nitrate is susceptible to leaching. It has a low nitrogen content of about 16.5% and, consequently, is costly to transport. The adverse effects of sodium on the soil have contributed to an overall decline in sodium nitrate use during the last century.

Calcium Nitrate

Calcium nitrate $[Ca(NO_3)_2]$ was one of the first materials produced from synthetically-fixed nitrogen by a process developed in Norway. This process involved electric arc fixation of elemental nitrogen. Calcium nitrate is still produced in Norway today, but the nitric acid required is derived from anhydrous ammonia. Greater use of calcium nitrate is prevented by the high cost per unit of nitrogen. Calcium nitrate contains only about 15.5% nitrogen, but is nevertheless an excellent source of nitrogen, providing both soluble nitrate and calcium.

Nitrogen Solutions

The last two decades have seen a rapid increase in the use of nitrogen solutions, and two distinct classes are available. The classification is based upon the presence or absence of free ammonia within the aqueous solutions. Those that contain free ammonia are referred to as pressure solutions, and those without free ammonia are named nonpressure solutions.

Nonpressure solutions are derived primarily from ammonia nitrate and urea but other materials, such as ammonium sulphate and calcium nitrate, may also be used. Nonpressure solutions can be applied as a surface dressing or they can be injected. On the other hand, pressure solutions can only be applied by injection methods appropriate for anhydrous ammonia. Pressure solutions always contain ammonia and may contain ammonium nitrate, urea, ammonium sulphate or calcium nitrate. Little use is made of pressure solutions for direct application, as they are primarily used in the production of compound fertilizers.

There are many advantages which have led to an increased use of nonpressure nitrogen solutions. These advantages are outlined by the IFDC (1979):

1. They are easy to handle and apply
2. They can be more uniformly applied to the soil
3. Pesticides can be mixed into the solutions and applied at the same time
4. They can be injected into irrigation systems
5. They are less hazardous and more economical to transport
6. They need only low-cost storage facilities
7. The solutions are useful for making NPK fluid-type mixtures
8. The cost of production is lower than for most solid sources of nitrogen
9. They are safer to handle than anhydrous ammonia

The applicators used to broadcast nitrogen solutions are available in a range of sizes, with the larger applicators being capable of applying fertilizer solution at a rate of 0.71 hectares per minute. High-flotation type applications also minimize compaction of the soil during fertilizer application and are suitable for use even during wet periods.

Slow-release Nitrogen Fertilizers

Slow-release nitrogen fertilizers are replacing more conventional fertilizers in some circumstances. In forest nurseries, for example, nitrate-induced iron chlorosis may be corrected by using a slow-release nitrogen source (Allen, 1982). Slow-release fertilizers have been extensively reviewed by Hauck and Koshino (1971). They are characterized by their ability to release nutrients over an extended period of time. Some common examples of slow-release nitrogen fertilizers are methylene diurea (IBDU), crotonylidene diurea (CDU) and sulphur-coated urea (SCU). The benefits include greater efficiency of nitrogen use, lower losses, and less frequent applications. However, their higher costs per unit of nitrogen have generally discouraged their widespread use in forestry.

Phosphorous Fertilizers

Rock Phosphate

Phosphate rock, the major ingredient in the manufacture of phosphorus fertilizers, is a trade name which refers to a variety of rock types composed primarily of phosphate minerals. Commercial deposits are used for fertilizer manufacture, direct application to the soil, or the manufacture of industrial compounds. Its level or grade of phosphorus is commonly expressed either as a percentage of phosphorus pentoxide (P_2O_5) or in terms of tricalcium phosphate [$Ca_3(PO_4)_2$]. The latter expression is known as the bone phosphate of lime of SPL. Commercial phosphate rock normally has a range of 28-38% P_2O_5 content (IFDC, 1979).

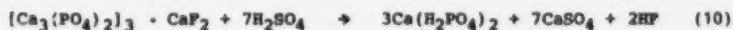
Phosphate rocks are classified into three broad categories based on mineral types, namely iron-aluminum phosphates, calcium-iron-aluminum phosphates and calcium phosphates. They can exist together as a natural weathering sequence with iron-calcium phosphates being the most weathered form. Economically, calcium phosphates are the most important group.

Calcium phosphates vary considerably in their chemical composition from that of fluorapatite [$Ca_{10}(PO_4)_6F_2$], the form which is most widely known. These differences in composition are reflected in the variable properties associated with their commercial concentration. Poor choices have sometimes been made concerning the types of phosphate rock used for direct application. This has led to a decline in use of phosphate rock as a directly-applied fertilizer (McClellan and Gremillion, 1980).

Calcium-iron-aluminum phosphates are an intermediate group which also vary widely in their composition. Crandallite [$CaAl_3(PO_4)_2(OH) \cdot 5H_2O$] and millisite [(NA,K) $CaAl_6(PO_4)_4(OH)_9 \cdot 3H_2O$] are the principal minerals in the group. They either exist together or with other types of phosphate minerals. The calcium-iron-aluminum phosphates are manufactured using nitric acid processes or they are thermally modified to produce direct application fertilizers. Similar methods are applied for manufacturing iron-aluminum phosphates. This latter group is characterized by such minerals as wavellite [$Al_3(PO_4)_2 \cdot (OH)_3 \cdot 5H_2O$], variseite ($AlPO_4 \cdot 2H_2O$) and strengite ($FePO_4 \cdot 2H_2O$).

Most ground rock phosphate used for crop production is processed to increase its phosphorus availability. The acid-treated compounds represent the major group of commercial phosphate fertilizers. It includes phosphoric acid, superphosphates, ammonium phosphates and nitric phosphates. Thermal phosphates are not as common because they are generally more expensive to produce or they contain a lower percentage of phosphorus. Basic slag or Thomas slag is an example of a heat-treated phosphate which is produced as a by-product in steel manufacturing.

The effectiveness of rock phosphate can be improved by mixing it with sulphuric acid and thereby producing normal superphosphate. The chemical reaction is:



Rock phosphate	Sulphuric acid	Monocalcium Phosphate	Gypsum	Hydrofluoric acid
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The low concentration of phosphorus in this material is a major disadvantage to its use. Nevertheless, significant amounts of this material are still used. An important use for it today is in the production of NPK fertilizer mixtures.

Phosphoric Acid

Wet-process phosphoric acid (H_3PO_4) is another product from the acidulation of phosphate rock with sulphuric acid. Higher concentrations or sulphuric acid are required than in the manufacture of normal superphosphate. Vacuum filtration separates the gypsum from the phosphoric acid. The acid can be used directly as a fertilizer, but there are handling problems due to its corrosive properties. Phosphoric acid can be applied simultaneously with anhydrous ammonia using special applicators. Furnace-grade phosphoric acid can be manufactured by first heating phosphate rock in an electric arc furnace. The elemental phosphorus produced is then oxidized and combined with water to produce a purer grade of phosphoric acid. This latter process is more costly and the phosphoric acid produced is normally used for industrial products rather than for fertilizers.

Triple Superphosphate

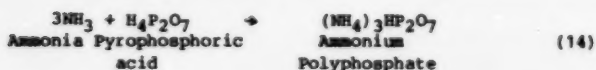
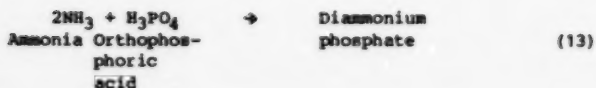
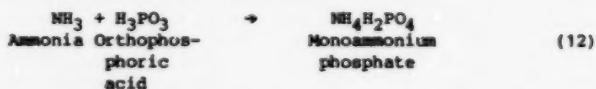
Triple superphosphate was developed to raise the phosphorus concentration of normal superphosphate from 7 to 9% phosphorus up to approximately 17 to 21% phosphorus. The process involves treating phosphate rock with phosphoric acid. The basic difference between normal and triple superphosphate is that there is no gypsum in triple superphosphate. Phosphorus availability remains largely unchanged. The reactions involved in the process are:



Rock phosphate	Phosphoric acid	Monocalcium phosphate	Calcium fluoride
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Ammonium Phosphate

Ammonium phosphates are important fertilizers, manufactured by reacting ammonia with phosphoric acid. The principal products are monoammonium phosphate, diammonium phosphate and ammonium polyphosphate. The reactions involved in their formation are:



They supply both nitrogen and phosphorus. Monoammonium phosphate consists of 11 to 13% nitrogen and 21 to 24% phosphorus. It mixes well with other nitrogen materials and may be used as a constituent of bulk blends. Diammonium phosphate has the added advantage of having a higher nitrogen content, in the 18 to 21% range. Polyphosphates have a higher phosphorus content and their chemistry results in their favourable reaction with metals such as magnesium, iron and zinc. This helps to prevent iron and magnesium from causing precipitation of their phosphates in liquid blends. It also allows liquid fertilizers to maintain higher concentrations of certain micronutrient elements such as zinc.

The trend towards higher costs for sulphur and sulphuric acid will likely increase interest in using nitric acid for the acidulation of phosphate rock. The main advantage of nitrophosphate processes is that calcium nitrate is produced as a by-product. The associated production costs can be applied, at least partially, to the nitrogen fertilizer product. This gives the nitrophosphate processes an economic advantage over processes that use sulphur acid.

Potassium Fertilizers

Potassium fertilizers are graded on the content of potassium oxide (K_2O), commonly known as potash. Similar to phosphorus pentoxide, potassium oxide is not absorbed by plants and, therefore, its widespread use by the fertilizer industry is an unfortunate convention. The principal potash minerals are sylvite, langbeinite, kainite and carnallite. The largest quantities of potash are mined from deposits of sylvinite, which is a mixture of potassium chloride and sodium chloride crystals.

The major potassium fertilizer used is potassium chloride (KCl), or muriate of potash, which is a crystalline, water-soluble material containing about 50% potassium. It is normally available at a lower cost than other potassium fertilizers and its high solubility and high potassium content make it a good choice for most crops.

Potassium sulphate (K_2SO_4) is more expensive than potassium chloride, but it is preferred for certain crops. It is mainly used where a low level of chloride is desired, for example, in potato growing. Excessive amounts of chlorides result in a rubbery, rather than crisp, potato chip. Potassium sulphate is a water-soluble crystalline salt that is a good source of sulphur (19% S) as well as potassium (42% K).

Other important potassium fertilizers include potassium-magnesium sulphate, potassium nitrate, potassium hydroxide and potassium phosphates. Potassium-magnesium sulphate is appropriate for use on magnesium-deficient soils. Potassium nitrate supplies appreciable amounts of nitrogen along with the potassium. High analysis, liquid fertilizers can be manufactured using potassium hydroxide and potassium phosphate. Unfortunately, the high costs associated with these fertilizers restricts their use.

For many years, manufacturers have been trying to produce a slow-release potassium fertilizer. Glass frits containing potassium have been used but again, costs are prohibitively high (Carlisle, 1982).

Calcium Fertilizers

Calcium is applied in significant amounts as a component of many mixed fertilizers. Rock phosphate and normal superphosphate are typical examples of mixed fertilizers which contain appreciable quantities of calcium. The trend today to higher nutrient element contents in the manufacture of mixed fertilizer has decreased the quantity of lime used as a filler. Nevertheless, many mixed fertilizers which are a good source of calcium are available for use.

Calcium is normally applied as agricultural lime for the purpose of adjusting the soil pH, rather than as a response to a known plant deficiency. Lime consists mainly of ground calcic limestone (CaCO_3) and sometimes dolomitic limestone [$\text{CaMg}(\text{CO}_3)_2$]. The finer the material is ground, the quicker it becomes effective. A very finely-ground lime costs more, however, and it is more susceptible to wind losses during application. Also, finely-ground lime is more readily leached and it will not remain effective for as long a period as coarser lime.

Magnesium Fertilizers

Magnesium is similar to calcium in that it is a constituent of many commonly-used mixed fertilizers. Finely-ground dolomite is an effective low-cost material for treatment of magnesium-deficient soils. It will reduce soil acidity and supplies additional calcium at the same time. If acidic soil conditions are desirable, then Epsom salt (MgSO_4) or potassium magnesium sulphate ($\text{K}_2\text{SO}_4 \cdot 2\text{MgSO}_4$) can serve as a magnesium source. These two sources contain water-soluble magnesium. They may be a good choice when a quick crop response is required to correct a magnesium deficiency.

Sulphur Fertilizers

Many fertilizer materials contain sulphur. The most commonly applied are the phosphates and sulphates. Sulphur compounds are normally used to correct alkalinity or salinity in soils, and large tonnages of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) are applied for these purposes. Elemental sulphur is also used. Increased use of more concentrated fertilizer has lowered the amount of sulphur being applied in fertilizer compounds. Substantial quantities of sulphur are being released to the atmosphere in pollutants from industrial processes. Most of this sulphur is eventually brought down to the ground by rainfall.

Sulphur can easily be added to solid or liquid fertilizers. It is normally mixed into granular compound fertilizers or bulk-blended fertilizers as ammonium sulphate, single superphosphate or calcium sulphate. Ammonia polysulphide, ammonium bisulphite and ammonium thiosulphate are the three major forms in which sulphur is added to nitrogen solutions or liquid-mixed fertilizers. Sulphur may also be applied in suspensions as fine elemental sulphur, ammonium sulphate or ground gypsum (IFDC, 1979).

Micronutrient Fertilizers

The micronutrients - boron, zinc, copper, iron, manganese, molybdenum and chlorine - are just as essential to crop growth as

macronutrients. When yields are increased by fertilization with macronutrients, the level of one or more of the micronutrients often limits growth. Under such circumstances, significant growth responses to micronutrient applications are possible. Their production and application is reviewed in detail by Mortvedt and Cunningham (1971).

The principal sources of micronutrients commonly applied as fertilizers are borax (sodium tetraborate decahydrate), sodium molybdate and the soluble sulphate salts which contain the metallic elements. Other sources include oxide and carbonate salts, frits (prepared by fusing micronutrient salts and silica into a glass or slag), and chelates. Chelates are complexes of micronutrients and organic compounds, a typical example being ethylenediaminetetraacetic acid. Some common micronutrient sources and their nutrient content are given in Table 5 (IFDC, 1979). In addition to those materials listed, many industrial by-products are used for their micronutrient content.

FERTILIZER USE IN CONVENTIONAL FORESTRY

Tamm (1968) provides a concise tabular summary of fertilizer development in Europe starting with studies by Ebermeyer on the effect of forest litter removal in Germany in 1876 (Table 6). Europeans were the first to study means of improving yields through forest fertilization. Evidence of soil deterioration, a lack of timber in some areas and higher stumpage values promoted the use of fertilizers in European forestry. There were early controversies over fertilizer use as described by Tamm (1968), for example, "there was often antagonism between foresters recommending the use of fertilizer, and those striving for what they called 'natural silviculture' by introducing 'soil improving tree species' such as oaks, maples and alders". Tamm (1968) believed such controversies were only of historical interest. Experts had apparently agreed that 'soil improving species' contributed to a sustained effect of fertilizers on some sites, but they were not as effective on poor sites without fertilizer additions. Alders and legumes had the ability to fix atmospheric nitrogen. However, they generally required higher levels of phosphorus and other nutrients, and higher soil pH, than were usually found on those sites most in need of improvement.

Discussion concerning the use of fertilizers versus biological means of soil improvement have not ended. In fact, they have increased in recent years. The situation over the use of red alder in the Pacific Northwest, for example, is described by Tarrant (1978) as "the fact remains that in our predominantly softwood timber economy, the value of red alder is today little appreciated".

In order to understand the development of fertilizer use, and the recent increased interest in biological methods of soil amelioration, one needs to examine fertilizer use in terms of the availability of inexpensive energy and the demand for forest products. Following the Second World War, research intensified on fertilization of nurseries and forest plantations. One reason for this increased activity was the higher demand for wood needed to repair damages caused during the war. Another reason was the widespread existence of plantations and second growth

Table 5: Some Typical Sources of Micronutrients

Element Supplied	Material	Formula of Principle Compound	Micronutrient Content (Percentage by weight of element)
Boron	Sodium tetraborate decahydrate	$\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$	11
	Sodium tetraborate pentahydrate	$\text{Na}_2\text{B}_4\text{O}_7 \cdot 5\text{H}_2\text{O}$	14
	Sodium tetraborate-pentaborate	-	20
	Colemanite	$\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 5\text{H}_2\text{O}$	16
Copper	Cupric oxide	CuO	79
	Cuprous oxide	Cu_2O	86
	Cupric sulphate monohydrate	$\text{CuSO}_4 \cdot \text{H}_2\text{O}$	35
	Cupric sulphate pentahydrate	$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$	25
Iron	Ferric sulphate monohydrate	$\text{Fe}_2(\text{SO}_4)_3 \cdot 9\text{H}_2\text{O}$	20
	Ferrous sulphate heptahydrate	$\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$	20
Manganese	Manganous carbonate	MnCO_3	46
	Manganous oxide (impure)	MnO	48
	Manganous-manganic oxide	Mn_3O_4	69
	Manganous sulphate monohydrate	$\text{MnSO}_4 \cdot \text{H}_2\text{O}$	24
Molybdenum	Ammonium molybdate	$(\text{NH}_4)_2\text{MoO}_4$	49
	Sodium molybdate (anhydrous)	Na_2MoO_4	46
	Molybic oxide (technical grade)	MoO_3	58-62
Zinc	Calcined zinc concentrate (impure)	ZnO	74
	Zinc carbonate (byproduct)	ZnCO_3	56
	Zinc oxide	ZnO	80
	Zinc sulphate monohydrate	$\text{ZnSO}_4 \cdot \text{H}_2\text{O}$	36
Chlorine	Potassium chloride	KCl	47
	Ammonium chloride	NH_4Cl	25

(from: IFDC, 1979)

Table 6: Forest Fertilizer Development in Europe

Time Period	Major Activity	Location
1865-1900	Recognition of forest nutrient cycle and of tree nutrient demands. Very few experiments.	Germany
1900-1925	Experiments of 'trial and error' type, less often based on analytical thinking.	Belgium Germany Denmark
1925-1960	Firm scientific foundation of forest nutrition work. Numerous experiments. Limited practical applications, particularly in Germany.	Germany Sweden Finland Czechoslovakia France Great Britain Norway Netherlands
1960-	Start of large-scale forest fertilization.	West Germany France Norway Finland Sweden East Germany

(from: Tamm, 1968)

forests growing on nutrient depleted soils. The post-war years up to the early sixties witnessed a dramatic increase in the number of published papers related to the subject of forest fertilization. Over two thousand reports on the study of soil fertility and its effect on tree growth were published during this period in the United States, Britain, Germany, Russia, Czechoslovakia, Japan and Scandinavian countries (Wilde, 1961). Mustanoja and Leaf (1965) listed over twelve hundred publications on forest fertilization issued between 1957 and 1964 alone.

Despite the enormous effort directed towards the use of fertilizers in forestry practice, only a small number of experiments provided clear and positive results (Assmann, 1970; Wilde, 1961). The major reasons for this situation were apparently:

1. Many reports denied the beneficial effects of fertilizers on growth
2. Improper experimental designs, e.g. small plot size, no controls
3. Unfounded extrapolations from basic data
4. Repetition of past experiments
5. Many experiments were established by practical foresters who lacked basic information on soils

Nevertheless, progress was made and companies started large-scale fertilization programs, beginning in the early 1960's. The availability of inexpensive chemical fertilizers and the rapid development of mechanical methods of fertilizer application encouraged this trend. Before the 1960's, most forest fertilization was done by hand. The introduction of forestry vehicles mounted with spinners and blowers helped progress considerably. However, the access of this type of equipment is restricted in older stands, or on rough or wet terrain. Both fixed-wing aircraft and helicopters are extensively employed in large-scale forest fertilization operations. The application methods used for forest fertilization in Sweden, for example, are shown in Table 7 (Holmen, 1979). Of the 135,000 hectares fertilized within Sweden in 1978, 94% were fertilized by aircraft. Although use of fixed-wing aircraft is the most popular method of applying fertilizers, greater use is being made of both helicopters and tractors. These changes are due to the high costs and difficulties in obtaining an even fertilizer spread using fixed-wing aircraft.

Table 7: Application Methods in Forest Fertilization in Sweden in 1974-78 and Distribution by Application Type

Application method	Year	Fertilized area (hectares) percent ^{1/}	
		Mineral Soil	Peatland
		ha	ha
Fixed-wing aircraft	1974	130 630 (78%)	218 (26%)
	1976	123 755 (66%)	113 (30%)
	1978	70 208 (53%)	437 (19%)
Helicopter	1974	35 433 (21%)	454 (54%)
	1976	61 991 (33%)	216 (57%)
	1978	54 612 (41%)	1 143 (48%)
Tractor	1974	735 (<1%)	60 (7%)
	1976	2 286 (1%)	28 (7%)
	1978	8 120 (6%)	684 (29%)
Broadcast	1974	551	106 (13%)
	1976	718	21 (6%)
	1978	358	99 (4%)

^{1/} As a % of either mineral soil or peatland fertilized.

(from: Holmen, 1979)

Nitrogen, phosphorus and potassium are the principal elements applied in operational fertilization programs. NPK mixtures are used on peat soils and infertile sandy soils especially in Europe, and for short-rotation forestry in Japan (Ballard, 1979). Phosphorus is applied to a range of soils in Europe, Australia, New Zealand and the southeastern United States. Nitrogen is widely used in established stands on mineral soils. Secondary macronutrients and trace elements are applied operationally only in some specific areas, as discussed by Atterson (1978).

Growth responses to fertilization can be spectacular when extreme nutrient deficiencies are corrected. Actual yield increases are site, species and element specific, with better responses from fast-growing species growing on nutrient-poor sites. Exceptional gains from phosphorus fertilization of *Pinus elliottii* in the southeastern United States (Pritchett and Smith, 1975) and *Pinus radiata* in New Zealand have been reported (Mead and Gadgil, 1978). Generally, volume increases from fertilization are more modest, ranging from 10 to 60 m³/ha (Ballard, 1979).

Forest fertilization in many countries is decreasing or gradually recovering from the "oil crisis" of 1973 (Table 8). Some examples of fertilizer usage on arable land are given in Table 9. Higher costs associated with the feedstock manufacturing and distribution of fertilizers is a significant factor in this decline. New Zealand is a notable exception to the downward trend; in the mid-seventies, there was an expansion of forest fertilization there, even though agricultural use of fertilizer materials declined during the same period. Ballard and Will (1978) felt that this increased use of fertilizers in forestry demonstrated the greater acceptance by forest managers of the value of forest fertilization. The expanded fertilizer program in New Zealand forestry was also encouraged by the introduction of a soil-testing service for predicting the need for phosphorus fertilizer at planting time and the start of a nitrogen fertilization program of *Eucalyptus* species in the Rotorua region.

Table 8: Annual Forest Area Fertilized (in Hectares)

Country	Time Period			References
	1971-72	1973-74	1975-76	
Finland	211,000	231,000	204,000	Uusitalo, 1979
Sweden	118,000	136,000	160,000	Hagner and leaf, 1973 National Board of Forestry, 1977
United States	71,000	142,000	91,000	Bengston, 1979
Japan	72,000	90,000	50,000	Kawana and Haibara, 1981
Great Britain	23,000	51,000	30,000	Mayhead, 1976
New Zealand	5,000	7,500	18,000	Ballard and Will, 1978
Canada	8,000	10,000	<15,000	Reed, 1978; Baule, 1973

Although many papers have been written showing tree growth responses to forest fertilization, few field studies have examined the effect of fertilizers on the soil. Those researchers who have related fertilizer applications to soil responses have generally limited their investigations to the study of only a few soil parameters. Some examples from North American studies are given in Table 10.

Many consequences of fertilizer application on forest soil processes are unknown or not fully explained. Conventional forestry has generally concentrated on determining significant growth responses to fertilization. With the higher risk of site degradation associated with intensive forestry, considerably more research effort is needed to determine the effects of intensive forestry on soil fertility. Techniques are also required to maintain or improve soil fertility of forest soils under intensive management.

Table 9: Fertilizer Usage on Arable Land (kg of N ha⁻¹ year⁻¹)

USA	43
United Kingdom	122
Netherlands	476
USSR	27
Spain	34
Egypt	133
Kenya	12
Nigeria	0.2
S. Africa	18
Brazil	13
India	11
Japan	155

(from: Bond in Newton *et al.*, 1977; FAO data)

LIMITATIONS ON FERTILIZER USE

A major limitation on fertilizer use in forestry today is the lack of good diagnostic techniques for predicting fertilizer needs. Ballard (1980) described three effective prescription systems available for operational programs, namely, soil analysis, tissue analysis and soil maps. These methods all supply important information, but they have major shortcomings. Soil maps provide important base data for making silvicultural prescriptions, but they cannot show the effects of subsequent management activities on soil fertility levels. Soil analysis has had limited use in forestry because of an inability of the method to predict response to fertilizers. Improvement in soil analysis predictions are possible, but require further work on extraction procedures and the development of prediction equations which account for such soil variables as effective rooting depth. Foliar analysis is a widely used diagnostic technique which integrates all factors affecting the tree's nutrient status.

Swan (1960, 1966) examined four techniques of diagnosis helpful in identifying soil nutrient deficiencies, namely, (1) visual symptoms, (2) soil analyses, (3) foliage analyses and (4) soil bio-assays. Each method contributed to a final diagnosis, but the bio-assay gave more reliable results. This technique involved growing seedlings under controlled conditions in samples of those soils under study. Growth responses to a range of nutrient levels were later measured and used to predict fertilizer needs.

The macronutrient weight proportions at maximum growth rate for seedlings of several forest species have been accurately estimated, as discussed by Ingestad (1979). These experiments were all carried out in

Table 10: Some Examples of Forest Response to Fertiliser in North America

Location	Characteristics (Age in Years)	Fertiliser Applied (kg/ha)	Forest Response (Duration 1+ Years)	References
Coniferous Species				
South Carolina, U.S.A.	<i>Pinus taeda</i> (17) Sandy-clay loam	Urea (56) Limestone (2240)	Positive Diameter Response (5) Higher soil pH and Ca levels	Van Lear, 1980
New York, U.S.A.	<i>Pinus abies</i> (19) Outwash sand	Potassium chloride (110)	Positive Volume Response (14) Increased N, Ca and Mg uptake	Forbes <u>et al.</u> , 1970
New York, U.S.A.	<i>Pinus resinosa</i> (20) Outwash sand	Potassium chloride (90)	Positive Height and Basal Area Response (12) Increased N, P, Ca and Mg uptake	Forbes <u>et al.</u> , 1970
Louisiana, U.S.A.	<i>Pinus elliptica</i> (3) Fine silt loam	Ammonium nitrate (403) Concentrated Superphosphate (95) Potassium chloride (64)	Positive Height and Value Response (6) High soil P at all depths sampled (6)	Shoulders and Tiarks, 1980
New York, U.S.A.	<i>Pinus resinosa</i> (37) Outwash sand	Potassium chloride (448)	g* leaching peaked one year later Infertilized plots	Marion and Leaf, 1977
Washington, U.S.A.	<i>Pseudotsuga menziesii</i> (30) Glacial Drift	Ammonium sulphate (494) Urea (494)	76% of N from urea and 88% from (NH ₄) ₂ SO ₄ leached beyond top horizon. Large release of K with N	Cole and Geesal, 1963
Oregon, U.S.A.	<i>Pinus ponderosa</i> (7) Loamy sand	Ammonium nitrate (400) Triple superphosphate (200)	Negative growth response to higher P levels. Higher soil N and P levels	Tarrant and Sillen, 1966
Vancouver Island, B.C., Canada	<i>Pseudotsuga menziesii</i> (25) Coarse textured soil	Ammonium nitrate (448) Urea (448)	Higher leaching rates with ammonium nitrate plus thinning (<1)	Perry and McCullough 1982
Virginia, U.S.A.	<i>Pinus taeda</i> (10) Silt loam	Limestone (4480) Superphosphate (933)	No growth response (10) Higher soil pH, Ca and Mg levels (10)	Moschler <u>et al.</u> , 1970
Quebec, Canada	<i>Pinus mariana</i> (65) Glacial till	Urea (448)	Positive growth response, higher soil pH (15) and NH ₄ -N levels (10), Lower C/N Rates (10)	Weetman <u>et al.</u> , 1980
Ontario, Canada	<i>Pinus banksiana</i> (45) Silt loam	Urea (300)	Positive growth response, higher soil pH, higher NH ₄ -N levels (1), higher N loss (30%) to atmosphere	Morrison and, Porter, 1977
British Columbia, Canada	<i>Pseudotsuga menziesii</i> (16) Gravelly sandy loam	Urea (448)	Positive growth response, higher soil pH values (1)	Ochters-Bostang and Ballard, 1978
Quebec, Canada	<i>Pinus banksiana</i> <i>Pinus sard</i>	Several N Sources (224)	Higher N levels in surface horizon when urea was applied	Camire and Bernier, 1981
Hardwood Species				
Kentucky, U.S.A.	<i>Platanus occidentalis</i> (1) Fine silt	Ammonium nitrate (169) Superphosphate (112)	Positive biomass response (5) Higher soil P, lower soil K and Ca (5)	Wittwer <u>et al.</u> , 1980
Pennsylvania, U.S.A.	Mixed <i>Quercus</i> spp. (50) Sandy loam	Hydrated lime (4942) Ammonium nitrate (445)	Positive value response (1) Higher soil pH and Ca (1)	Ward and Bowersox, 1970
Alaska, U.S.A.	<i>Populus tremuloides</i> (15) Silt loam	Ammonium nitrate (111) Triple superphosphate (55)	33% to 42% higher soil biological activity Higher surface organic matter levels	Van Cleave and Moore, 1978

the phytotron in Stockholm, Sweden. Details of the materials and methods followed were described recently by Ingestad and Lund (1979). The characteristic feature of the technique is that nutrients are supplied in fixed proportions to the nutrient solution at a rate comparable with the rate of consumption. Experimental results have already been successfully applied in greenhouse trials, but additional information is needed before results can be widely applied (Ingestad, 1974).

The Swedish research team is making significant progress towards developing efficient methods of using chemical fertilizers. Major findings, so far, include:

1. Optimum growth curves are exponential, not logarithmic as was previously reported
2. Deficiency symptoms appear when the nutrient status of a plant is rapidly changing from one level to another; however, the symptoms disappear once the plant is adapted to the new nutrient supply
3. Nutrient availability is the decisive factor in determining plant nutrition and growth, not the concentration of nutrients in the soil
4. Nutrient balance appears to be more important in determining growth response than absolute nutrient concentrations
5. Fertilizers must be applied in small amounts approaching the current mineralization rate, if they are to be efficiently absorbed and utilized

A simulation model was constructed to analyze the effects of both fertilization and the rate of mineralization on nutrient availability (Ingestad et al., 1981). The model has been tested using data from a *Pinus sylvestris* ecosystem study (Aronsson et al., 1977). Preliminary results obtained using the model are encouraging (Ingestad et al., 1981). Information gaps have been identified and include:

1. The need to test other fertilizer regimes
2. Better estimates of mineral requirements for maximum production are required
3. More detailed information on soil nitrogen pools and processes are needed
4. Further field studies are required, particularly to assist in understanding interactions between the biotic and abiotic processes in ecosystems

Other methods for determining nutritional status have been developed, and some may eventually be valuable for forest tree species (Keller, 1973). The possibility of monitoring nitrogenous compounds, enzymes or hormones in relation to nutrient deficiencies requires further investigation. Working with apple seedlings, for example, Hoffman and Samish (1971) found that optimum potassium supply was associated with low levels of free nitrogenous compounds. Putrescine was found to be closely linked with potassium nutrition as shown in Table 11.

Table 11: Potassium Concentration of Foliage, Relative Growth Rate^{1/}, and Putrescine Content of Apple Seedlings (Hoffman and Samish, 1971)

K	Rel. Growth Rate	Putrescine
%	%	ppm
0.43	68	115
1.15	100	8
1.76	88	50
2.56	71	118

^{1/} Growth rates are given relative to a maximum growth rate for seedlings with foliage having a low putrescine content.

(from: Keller, 1973)

The situation today finds companies committed to large-scale forest fertilization programs that have proceeded even without confidence in the system used for diagnosis of nutrient deficiencies. This condition is evident from the numerous requests from management for researchers to provide information, after the fact, to justify operational fertilization programs (Ballard, 1980).

The concern over the possibility of greater insect and disease damage following fertilization is another important limitation which restricts the expansion of forest fertilization operations. For example, evidence of increased damage from fusiform rust and pitch canker in the southeastern United States have resulted in a re-evaluation of fertilizer practices. Fortunately, the effect of fertilizers on damage levels is believed to be considerably less than was originally suspected (Pritchett and Smith, 1975). There is still uncertainty, however, concerning the effects of fertilization on insect and disease epidemics. Many factors are involved and must be considered in an attempt to determine the role of fertilizers in disease outbreaks. This makes prediction of any fertilizer effects very difficult.

Fertilization may help to reduce insect and disease problems. Potassium appears to be a particularly important element in this regard. The severity of attack by leaf blotch *Marssonina* on poplar leaves, as an example, can be closely correlated to the potassium level in the leaves (Table 12). Low potassium levels in poplar leaves corresponded with areas suffering from severe leaf blotch damage.

While applications of a single element, particularly nitrogen, can increase a tree's susceptibility to insects and diseases, it appears that adding additional nutrient elements to offset any nutrient imbalances can eliminate susceptibility problems created by the addition of only a single nutrient element (Baule, 1973). Nutrient imbalances can lead to a rise in metabolites which favour fungal attack.

Table 12: Connection Between Degree of Attack by Leaf Blotch (Marssonina) and Nitrogen and Potassium Content of Poplar Leaves

Degree of attack	Nutrient content in % of dry matter					
	1960	N 1961	1962	1960	K 1961	1962
Severe	2.86	2.38	2.31	0.62	0.83	1.30
Weak	1.47	2.53	2.35	1.97	2.96	3.04

(from: Baule, 1973)

If present trends continue to further restrict the use of pesticides and fungicides, then fertilizers could play a big role in future insect and disease control. Fertilizer use would then form part of an integrated pest management program. Prior to fertilizers being accepted for this role, greater knowledge of their influence on host susceptibility and the population dynamics of harmful organisms at critical stages in stand development is needed (Ballard, 1981).

World fertilizer consumption is continuing to increase (Figure 1). Total world consumption of fertilizers in 1979-80 amounted to 111.7 million metric tonnes (FAO, 1981). This represents an increase of 3.3% over the previous year. Meanwhile, fertilizer production rose by 4%. These figures are significantly lower than Sorenson's (1977) estimate that to maintain the current food situation, an 11% annual increase in fertilizer production is necessary. The downturn reflects the continually escalating costs of energy and the effect it is having on the costs of raw materials and fertilizers.

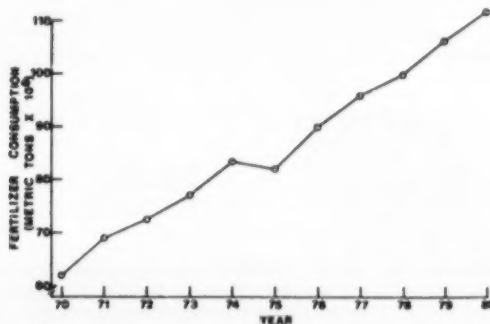


Figure 1: World Fertilizer Consumption (N, P₂O₅ and K₂O Combined), 1970-82

(from: Harris and Harre, 1979)

There are strong signs that the present production surplus of nitrogen will rapidly disappear. World nitrogen consumption in 1979 was 51.4 million metric tonnes while 51.6 million metric tonnes were produced. The high cost of feedstock is causing closures of a significant portion of the naphtha-based ammonia capacity. Meanwhile, the demand for nitrogen fertilizers is increasing in such major countries as India and China. It appears probable that nitrogen fertilizer prices will continue to rise in the future.

Forest fertilization activity has so far survived, despite the steadily increasing costs of fertilizer materials. The effect of fertilizer price increases on particular countries will vary according to their fertilizer production and consumption levels. Appendices I-III give the status of some countries in nitrogen, phosphorus and potash production, consumption and trading. Those countries which must import feedstock, or have little production capacity themselves, will suffer greatest as prices rise. This is particularly true for nitrogen which is characterized by an inelastic demand function. The need for nitrogen to maintain yields and its low residual level in soils help to maintain a high demand even as nitrogen prices rise. Such is not the case for phosphorus and potash. The demand for these decreases as their prices begin to rise. The result of this situation is that while raw material costs to produce phosphates and potash are high, the price of their fertilizer products has remained relatively low. Unless circumstances change, there will be little incentive to expand production capacity. In fact, Japan has already drastically cut its capacity to produce both ammonia and phosphate because of high raw material costs.

Fertilizers are generally considered to be finite resources and their eventual scarcity is cause for concern. World rock phosphorus could be used up within four-hundred years (Atterson, 1978), but such predictions lack precision. The major world phosphate reserves and resources are listed in Appendix IV (Cathcart, 1980). Reserves are those deposits which can be mined at a profit under today's economic and technological constraints. Resources are deposits which are considered to be of a reasonable extent or grade, but are not marketable under today's conditions. It is implicit from these definitions that both reserve and resource levels are constantly changing as economic and technological developments occur. The better grades of phosphate rock are being mined now, but as these deposits become exhausted, fertilizer prices are likely to rise substantially.

The manufacture of chemical fertilizers is energy intensive. This is particularly true of nitrogen fertilizers. The energy needed in the production of some types of fertilizers are listed in Table 13 (Davis and Blouin, 1977). Other authors (Smith and Johnson, 1977) have described the low energy input to high energy output relationships associated with intensive forestry. For example, intensive silviculture including fertilization was found to be about ten times as efficient as corn production in agriculture. Miller and Fight (1979) estimated that 10.6 units of energy are provided for each unit expended in fertilizing Pseudotsuga menziesii. While such ratios are impressive, they are no justification for forest fertilization (Beuter, 1979).

Table 13: Total Energy Required for Production of Major Types of Fertilizers

Nitrogen	Energy per ton N ($\text{kJ} \times 10^6$)
Ammonia	44
Solid Urea	52
Urea Solution	47
Solid Ammonium Nitrate	53
Ammonium Nitrate Solution	49
Phosphate	Energy per ton P_2O_5 ($\text{kJ} \times 10^6$)
Wet-process Acid	11
Triple Superphosphate	12
Normal Superphosphate	2
Potassium	Energy per ton K_2O ($\text{kJ} \times 10^6$)
Potassium Chloride	4

(from: Davis and Blouin, 1977)

Chemical fertilizers are not efficiently utilized. Plant uptake of nitrogen fertilizers, for example, ranges from 40 to 70% of that applied (Konkles, 1973; Nelson et al., 1977). Nitrate is susceptible to both leaching and denitrification losses. Gaseous losses from urea applications to forest soils may amount to 30% or more of the nitrogen applied (DeBell, 1979). Urea applied at a rate of 400 kg ha^{-1} resulted in ammonia volatilization losses of $4 \text{ kg ha}^{-1} \text{ day}^{-1}$ from an 18-year-old Pinus elliotii var. elliotii plantation (Boomsma and Pritchett, 1979).

Fertilizers are a potential source of serious pollution. As previously mentioned, pollution can result from the production of fertilizers e.g. ammonium nitrate, and fertilizers applied to forest lands can contribute to eutrophication of water or to unacceptable levels of nitrate in ground water (Salonen, 1980). Frequent low applications instead of single high applications of chemical fertilizers are unlikely to cause any harmful effects on soil or water. There is uncertainty, however, about repeated fertilization using urea as a nitrogen source. It may result in microorganisms producing an excessive amount of leachable nitrates. This may be particularly important when clear-felling fertilized stands, an operation which also causes nitrate mobilization (Wiklander, 1977).

Adding fertilizers can result in significant soil acidity changes which can destroy certain species of microflora and microfauna (Hill et al., 1975). Some organisms are favoured to the detriment of others. Soil organisms are directly responsible for the release of most nutrients required by plants. It is not clear how these organisms are affected by fertilization.

The application of nitrogen fertilizers will create conditions favourable for an overall increase in microbial activity (lower carbon/nitrogen ratio). The result of this activity will be increased CO_2

loss through respiration. Over the long term, this priming effect could result in significantly reduced levels of organic matter. Organic matter losses will adversely affect soil moisture and nutrient holding capabilities (cation exchange capacity will be lowered). Unless this situation is corrected, nitrogen fertilization could lead to a lowering of soil productivity.

Chemical fertilizers are likely to be more effective if they are used in conjunction with organic means of soil improvement. Spratt and McIver (1979) found significant yield increases of wheat fertilized with both barnyard manure and monoammonium phosphate as compared to areas treated with monoammonium phosphate. The yield differences have become progressively larger in this long-term experiment which has now run for over thirty years. These yield differences are the result of an improved soil structure created by manure application, possible exhaustion of sulphur and zinc reserves on the monoammonium phosphate treated site, and a possible build-up of impurities such as molybdenum from the monoammonium phosphate.

Interest in maintaining soil fertility by biological means is increasing. Nitrogen fixation by legumes and non-leguminous symbiosis, for example, can add significant quantities of nitrogen to the soil each year (Table 14). Nitrogen fixation can be encouraged by forest managers by inoculation and provision of favourable substrates for microorganism activity once more is known about the processes and organisms involved. Non-leguminous tree and shrub nitrogen-fixing symbioses, such as that between *Alnus* and *Frankia* can be used by managers to improve nitrogen income and soil organic matter levels. Many problems of competition and control between nitrogen-fixing species and crop species exist, however, and remain to be solved.

Table 14: Summary of Income of Nutrients to Forest Ecosystems

	(kg ha ⁻¹ yr ⁻¹)			
	N	P	K	Ca
Precipitation	1.9-41.4 (mean c. 5.0)	0.1-2.9 ⁴ / (mean c. 1.0)	0.6-12.0 (mean c. 2.5)	0.9-23.5 (mean c. 6.0)
Mineral weathering	-	0-tr ² / 	tr-11.1 ² / 	tr-86 ² /
N-fixation	0-300 ¹ / 	-	-	-
Atmospheric Aerosols	?	?	5-7 ³ / 	4-6 ³ /

¹/ For free-living N-fixing organisms 1-5 kg ha⁻¹ yr⁻¹
For *Alnus* and Legume symbioses 100-300 kg ha⁻¹ yr⁻¹

²/ Very approximate. Data open to question. (tr represents trace levels)

³/ Scotland and Germany data

⁴/ Estimates usually low due to sampling difficulties

(from: Carlisle, 1980)

PRINCIPLES INVOLVED IN THE EFFICIENT USE
OF FERTILIZERS IN FORESTRY

The efficient use of fertilizer depends not only on the diagnosis of soil deficiencies and the application of elements that are lacking, but also on a full understanding by the forester of the processes of forest soils and their interrelationships with trees and other vegetation. While it is not possible for the forester to take into account a multitude of interacting factors without computer simulation, he can at least be guided by a few principles, such as:

- (a) The purpose of fertilization is to supply just sufficient nutrients to supply the tree's need for growth and good health, as well as to maintain or improve the productivity of the site.
- (b) The pursuit of maximum growth at the cost of upsetting the balance of other nutrients and reducing organic matter levels is short-sighted, as farmers have found on the Prairies. Soil fertility is as much an asset as tree growth. A short-term increase in yield does not necessarily mean that all is well with the soil.
- (c) When fertilizers are added to the soil, they effect the soil organisms as well as the trees, and this can be desirable or undesirable depending upon the circumstances. This particularly applies to nitrogen which can trigger excessive nitrification and reduction of organic matter levels. Reduction of organic matter can be a benefit if levels are excessive, or harmful if levels are sufficient or too low to maintain adequate ion exchange capacity. As in many fields, a good response to a little fertilizer does not indicate a better response if a lot is added.
- (d) Heavy fertilizer nutrient losses in the order of 40 to 50% can result when the nutrient is in a mobile ionic form (e.g. NO_3^-) or can accelerate soil processes leading to this ionic form or mobile gases (e.g. N_2 and N_2O). Excessive application of fertilizers can literally mean money down the drain.
- (e) The soil is not a simple hydroponic system. It has active macro-, meso-, and microbiotas interacting with each other, the soil matrix and solution, the physiochemical constituents, and the micro-environment. It is a system in balance and fertilizers, with their potent chemical components, should be applied with this in mind.
- (f) Fertilization is only one of the tools a forester can use to maintain soil fertility and site productivity. It is one facet of total soil management. Good silviculture and harvesting techniques can reduce nutrient losses by leaching and gaseous loss. Soil management by manipulation of the vegetation is also a potent tool. Similarly, the biological processes of the soil and plant-microorganism symbioses, such as mycorrhizae and nitrogen-fixing systems (Fortin and Perinet, 1982; Carlisle, 1980), can be utilized and manipulated once they are better understood. Nitrogen-fixing symbioses can fix up to $300 \text{ kg ha}^{-1} \text{ yr}^{-1}$ of atmospheric nitrogen in an NH_3 form the plants can use, far more than is needed in fertilization. These systems tend to be

self-regulatory since the fixation process stops when nitrogen supplies reach a certain level. Van Hook *et al.* (1982) described how fertilization, strip-cutting, harvesting in the dormant season, cable logging, longer rotations, etc., can all be used to moderate undesirable effects of harvesting and other activities on the soil.

- (g) Any cost/benefit assessment of a fertilizer treatment must take into account the benefits of increased yield, shortened rotations, and maintenance of site productivity. The latter is difficult to assess but so are the many intangible benefits of forest management that need to be taken into account in economic exercises if forestry's true worth is to be recognized.
- (h) The timing of fertilization is vital; the site should be planted, and if necessary fertilized, as soon as possible after harvesting. This is particularly the case with nitrogen. When a site is clear-cut and disturbed, there is a surge of mobile nutrients. Mineralization and nitrification increase and, unless the site is rapidly recolonized to lock up the released nitrate (NO_3^-), this ion can be lost by leaching or as gases (NH_3 , N_2 , N_2O), particularly if denitrification follows. Leaving a site unplanted means much more nitrogen must be replaced. Waring (1973) demonstrated that the yield of *Pinus radiata* was reduced when the application of fertilizers after planting was delayed (Figure 2).

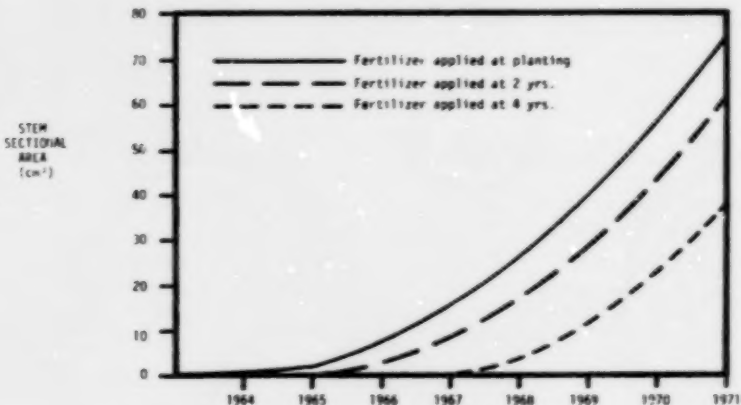


Figure 2: Increase Over Controls in Stem Cross-Sectional Area of *Pinus radiata* Seedlings from the Application of Nitrogen and Phosphorus Fertilizers

(from: Waring, 1973)

- (i) When phosphorus is at a low level in the soil, or is in a form that is not readily available, adding even a small amount of phosphorus will permit the formation of mycorrhizae which can increase

phosphorus uptake from the soil minerals. Adding a great deal of phosphorus may be unnecessary, although a considerable amount is often needed on organic soils. Taking into account the impact of fertilizers on the soil biota can save money.

- (j) In the planning of fertilization programs, it is essential that the forester thinks in terms of both tree and soil management. An increase in the soil science component of forestry curricula, including physical, chemical, and biological aspects, as well as site and soil classification, would help foresters to adopt this broader approach.
- (k) When planning fertilizer experiments to study the responses of the trees, recording the physical, chemical and biological soil responses would greatly strengthen the information base upon which fertilizer programs are designed. The empirical approach has served its purpose and now it is necessary to look a little deeper into processes and interrelationships.
- (l) While the above statements apply mainly to forest soils, they also apply to the fertilization and management of soils of high fertility, such as the agricultural soils used for mini- and short-rotation forestry. High demands by vegetation and site disturbance can rapidly reduce nutrient and organic matter levels of even these soils.

Simply adding fertilizers, particularly nitrogen, can rapidly reduce organic matter levels when applied injudiciously without regard for the processes involved. Consequent reduction of ion exchange capacity will increase fertilizer losses which, in the case of nitrogen, are already high.

- (m) Chemical fertilizers (e.g. calcium) can affect the pH of the soil and thereby affect leaching rates, nutrient availability (Figure 3) and soil microorganism activity. The pH following fertilization should be recorded, and the probable effects assessed for the particular site in question.
- (n) Application of fertilizers is governed by the soil type and the response of the trees to it. Definition of forest soils varies from country to country. In some countries, such as Britain, chemical analysis of soils, as well as recording soil structure, are done on a routine basis. In other countries, such as Canada, forest soils are defined on semi-qualitative bases. Fertilizer prescriptions should be based on more detailed chemical and physical analysis than is generally available.

NEEDS FOR RESEARCH AND FIELD TESTING

The amount of information available on forest soils and their processes is small compared with agricultural soils. If fertilization is to be effective, much more data of both a basic and a site-specific nature is needed. Although a great many empirical fertilizer experiments have been carried out and growth responses recorded, relatively little is known

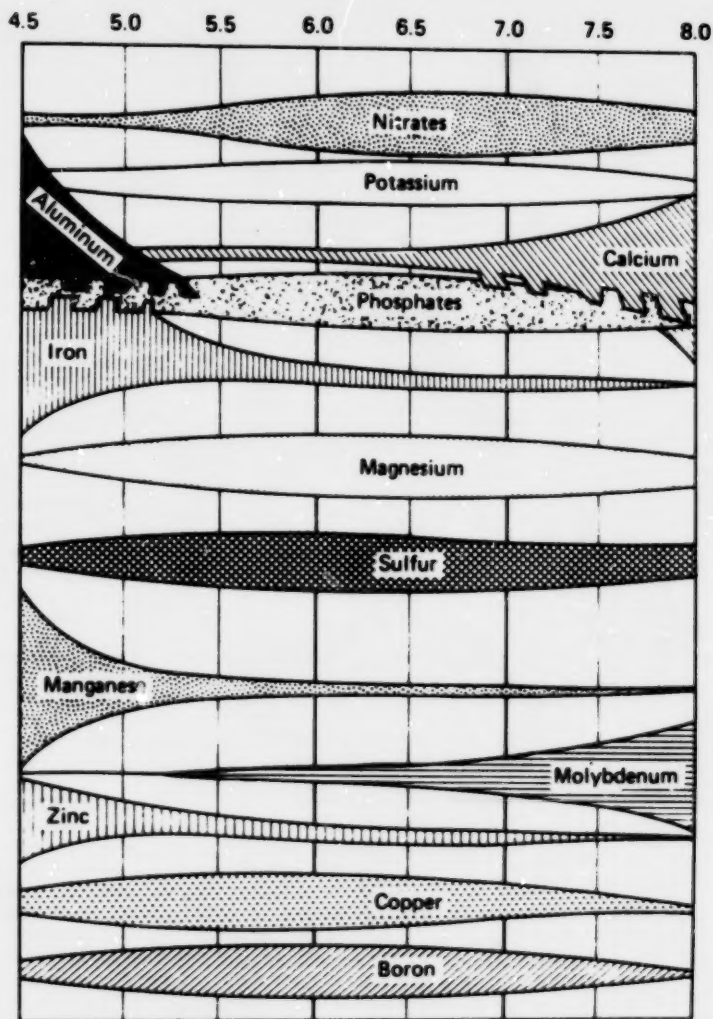


Figure 3: Effect of Soil pH on Nutrient Availability

(Note: The wider the band the greater the availability)

(from: Pollett et al., 1981)

about the interaction of the elements applied with each other or the soil biota, nor about their long-term effects on the sites. Consequently, decisions on which fertilizer to apply and when and where to apply it, have been based on empirical tree growth responses rather than the biology of the plants and the soil processes. Reliance on short-term tree growth responses as indicators of soil improvement can be misleading.

It is suggested that:

1. Basic research should be carried out, both in the laboratory and in the field, on the amounts of nutrients required by forest trees, taking into account the interaction between the elements.
2. Experiments should be established to examine the effects of fertilization on (a) the soil organisms concerned with organic matter mineralization, nitrification and denitrification, (b) nitrogen-fixation, (c) mycorrhizae formation, and (d) physio-chemical characteristics of the soil that effect soil fertility.
3. Slow-release fertilizers should be developed to avoid the overload of soils with elements and the upset of the balance of soil nutrients.
4. Ways should be found to coordinate fertilization programs with silvicultural logging techniques and biological soil management techniques, in order to maintain levels of nutrient elements without degrading soil organic matter and other soil attributes contributing to soil fertility.
5. The forester should include in his working plans, the dual approach of tree and soil management to optimize yield and yet maintain site productivity in the long term, using the array of chemical, microbiological, and silvicultural tools at his disposal.
6. Research should be carried out on the effects on soil fertility of delaying reforestation and fertilization for different periods on clear-cut sites.
7. Additional research should be carried out on the effects of fertilization on insect and disease resistance in forest species.
8. Experiments should be established to integrate and compare chemical fertilizer use with other forms of fertilization, e.g. waste sludge applications or wood ash application such as that described by Paavilainen (1980).

CONCLUSIONS

1. Much remains to be learned about the nutrient requirements of forest trees. We know those elements which are essential to plant growth, but many of their roles and interactions within the plant are not clearly understood. This is particularly true for the micronutrients.

2. Plants require a 'balanced' nutrition for proper growth and development. The optimal proportions of nutrient elements for obtaining maximum growth have only been determined for seedlings of some forest species.
3. Intensive forestry, which is characterized by shorter rotations, closer utilization levels and more intensive culture, places greater stresses on forest soils. Nutritional problems are more likely to develop as forest management intensifies.
4. Computer simulation modelling is a useful technique for investigating effects of management on soil processes and making predictions on the long-term consequences of soil processes on soil fertility.
5. The use of chemical fertilizers on a large scale is a relatively recent activity, beginning in forestry in the 1960's. However, even today every small forested area is actually fertilized. The role of chemical fertilizers within intensive forest management systems is not clearly defined, but interest in their use is likely to increase.
6. A wide range of chemical fertilizers is available. They each have their own chemical and physical characteristics, and costs, which need to be considered before they are used. Decisions on which fertilizers to apply, and when and where to apply them have been based on empirical tree growth responses rather than the biology of the plants and soil processes.
7. There are important limitations associated with the use of chemical fertilizers. They are often costly, energy demanding, relatively scarce, and may cause pollution problems. In forestry, there is a lack of good techniques for proper diagnosis of nutrient deficiencies.
8. Nitrogen fertilizer applications may result in heavy losses from ammonia volatilization, nitrate leaching or denitrification and may cause undesirable changes in soil pH and reductions in organic matter levels.
9. Chemical fertilization is only one tool a forester can use to maintain soil fertility; it is one facet of total soil management. Good silviculture and harvesting techniques can reduce nutrient losses. Biological processes such as nitrogen-fixation, and the use of mycorrhizae, can be utilized to improve soil fertility once they are better understood.
10. Ways are needed to stimulate the natural processes of nutrient accretion and cycling. As pointed out by Bengtson (1979), "highly selective use of fertilizers as catalysts for these processes rather than as massive substitutes for or shortcuts to them" is required.

REFERENCES

- Aber, J.D., D.B. Botkin and J.M. Millilo. 1978. Predicting the effects of different harvesting regimes on productivity and yield in northern hardwoods. *Can. J. For. Res.* 9: 10-14.
- Alexander, M. 1977. *Introduction to soil microbiology*. John Wiley & Sons Inc., Toronto, Canada. 467 pp.
- Allen, S.E. 1982. Slow-release nitrogen fertilizers. Paper presented at Nitrogen in Crop Production Symp., May, 1982, Sheffield, Alabama.
- Aronsson, A., S. Elowson and T. Ingestad. 1977. Elimination of water and mineral nutrition as limiting factors in a young Scots pine stand. Swedish Coniferous Forest Project, Techn. Rep. 10: p. 1-138.
- Assmann, E. 1970. *The principles of forest yield study*. Pergamon Press, Toronto, Canada. p. 506.
- Atterson, J. 1978. Current fertilizer use in plantations in ecology of even-aged plantations. (E.D. Ford, D.C. Malcolm and J. Atterson (eds.)) *IUFRO Proc.*, Edinburgh. p. 313-323.
- Ballard, R. 1979. Use of fertilizers to maintain productivity of intensively-managed forest plantations. *In Impact of Intensive Harvesting on Forest Nutrient Cycling Symp. Proc.* College of Env. Sci. and For., Syracuse, New York. p. 321-342.
- Ballard, R. 1981. The means to excellence through nutrient amendment. *In Forest-to-Mill: Challenges of the Future. Proc. Weyerhaeuser Science Symp.*, Tacoma, Washington. p. 159-200.
- Ballard, R. and G.M. Will. 1978. Past and projected use of fertilizers in New Zealand forests. *N.Z. J. For. Sci.* 8(1): 15-26.
- Baule, H. 1973. Effect of fertilizers on resistance to adverse agencies. *In Proc. FAO/IUFRO Intern. Symp. on Forest Fertilization*. Ministry of Agriculture, Paris. p. 181-214.
- Baule, H. 1973. World-wide forest fertilization: its present state and prospects for the near future. *Potash Review* 22(21): 1-23.
- Bengston, G.W. 1973. Fertilizer use in forestry: materials and methods of application. *In Proc. FAO/IUFRO Intern. Symp. on Forest Fertilization*. Ministry of Agriculture, Paris. p. 97-153.
- Bengston, G.W. 1979. Forest fertilization in the United States: progress and outlook. *J. For.*, April 1979. p. 222-229.
- Beuter, J. 1979. Forest fertilization and the economics of perpetual motion machines. *In Symbiotic Nitrogen Fixation in the Management of Temperate Forests, Symp. Proc.*, Oregon State University. p. 4-13.
- Bond, G. 1977. The importance of the biological fixation of nitrogen. *In Recent Developments in Nitrogen Fixation*. (W. Newton, J.R. Postgate and C. Rodriguez-Barrueco (eds.)) Academic Press, London, xvii-xxiii.

- Bonneau, M. 1973. The state of research on forest nutrition. In Proc. FAO/IUFRO Intern. Symp. on Forest Fertilization. Ministry of Agriculture, Paris. p. 1-21.
- Boomsma, D.B. and W.L. Pritchett. 1979. Nitrogen losses for urea and ammonium sulphate applications to a slash pine (Pinus elliotii var. elliottii Engelm.). In Impact of Intensive Harvesting on Forest Nutrient Cycling Symp. Proc., College of Env. Sci. and For. p. 390. (Abstract).
- Camire, C. and B. Bernier. 1981. Nitrogenous fertilization of a jack pine forest. Can. J. For. Res. 11(2): 413-421.
- Carlisle, A. 1980. Forest exploitation and environmental objectives. 11th Commonwealth Forestry Congress, Trinidad. p. 39.
- Carlisle, A. 1982. Personal communication.
- Cathcart, J.B. 1980. World phosphate reserves and resources (Chapter 1). In The Role of Phosphorus in Agriculture. (M. Stelley (ed.)) Amer. Soc. of Agronomy, Madison. p. 1-18.
- Clarkson, D.T. and J.B. Hanson. 1980. The mineral nutrition of higher plants. Ann. Rev. Plant Physiol. 31: 239-298.
- Cole, D.W. and S.P. Gessel. 1963. Movement of elements through a forest soil as influenced by tree removal and fertilizer additions. In Forest-Soil Relationships in North America. (C.T. Youngberg (ed.)) Oregon State University Press, Corvallis. p. 95-104.
- Collings, G.H. 1949. Commercial fertilizers. Their sources and uses (4th ed.) The Blakiston Company, Toronto, Ontario. 498 pp.
- Davis, C.H. and G.M. Blouin. 1977. Energy consumption in the U.S., chemical fertilizer from the ground to the ground. In Agriculture and Energy. (William Lockeretz (ed.)) Academic Press, Inc., New York. p. 315-331.
- DeBell, D. 1979. Future potential for use of symbiotic nitrogen fixation in forest management. In Symbiotic Nitrogen Fixation in the Management of Temperate Forests Symp. Proc., Oregon State University. p. 451-466.
- Epstein, E. 1972. Mineral nutrition of plants: principles and perspectives. John Wiley & Sons, Toronto, Canada. 412 pp.
- F.A.O. 1981. FAO Fertilizer Yearbook, Vol 30. Food and Agricultural Organization of the United Nations, Rome. 146 pp.
- Follett, R.H., L.S. Murphy and R.L. Donahue. 1981. Fertilizers and soil amendments. Prentice-Hall, Inc., New Jersey. 557 pp.
- Fornes, R.H., J.V. Berglund and A.L. Leaf. 1970. A comparison of the growth and nutrition of Picea abies (L.) Karst. and Pinus resinosa Ait. on a K-deficient site subjected to K fertilization. Plant and Soil 33. p. 345-360.

- Fortin, J.A. and P. Perinet. 1981. Uses of nitrogen fixation and other root symbiosis for biomass production. ENFOR Progress Report. Dept. of Env. 63 pp.
- Hagner, S. and A.L. Leaf. 1973. Fertilization of established forest stands. In Proc. FAO/IUFRO Intern. Symp. on Forest Fertilization. Ministry of Agriculture, Paris. p. 243-270.
- Hall, A.D. 1948. Fertilizers and manures. Wyman and Sons Ltd., London. 333 pp.
- Harris, G.T. and E.A. Harre. 1979. World fertilizer situation and outlook - 1978-85. International Fertilizer Development Centre and Tennessee Valley Authority, Muscle Shoals, Alabama. 27 pp.
- Hauck, R.D. and M. Koshino. 1971. Slow-release and amended fertilizers. In Fertilizer Technology and Use (2nd ed.) (R.A. Olson et al. (eds.)) Soil Sci. Soc. Amer., Inc., Madison, Wisconsin. p. 455-494.
- Hignett, T.P. 1974. Recent developments in fertilizer production technology and economics with special reference to ammonia and compound fertilizers. IFDC Extensive Bull. No. 40. p. 71.
- Hignett, T.P. 1979. Transportation and storage of ammonia. In Proc. 29th Annual Fertilizer Round Table, Oct. 30 - Nov. 1, 1979, Washington, D.C. p. 23-37.
- Hill, S.B., L.J. Mety and M.H. Parrier. 1975. Soil mesofauna and silvicultural practices. In Bernier, B. and C.H. Winget. 1975. Forest Soils and Forest Land Management P.U.L., Quebec. p. 119-135.
- Hoffman, M. and R.M. Samish. 1971. Free amine content in fruit tree organs as an indication of the nutritional status with respect to potassium. In Recent Advances in Plant Nutrition (R.M. Samish (ed.)) Gordon & Breach Sci. Pub., New York. 1: 189-204.
- Holmen, H. 1979. Forest fertilization in Sweden, 1978. Swedish Univ. of Agr. Sci., Umea. 9 pp.
- I.F.D.C. 1979. Fertilizer manual. International Fertilizer Development Center, Muscle Shoals, Alabama. p. 353.
- Ingestad, J. 1974. Towards optimum fertilization. Ambio 3(2): 49-54.
- Ingestad, T. 1979. Mineral nutrient requirements of Pinus slyvestris and Picea abies seedlings. Physiol. Plant. 45(4): 373-380.
- Ingestad, T. and A. Lund. 1979. Nitrogen stress in birch seedlings. Physiol. Plant. 45(1): 137-148.

- Ingestad, T., A. Aronsson and G. Agren. 1981. Nutrient flux density model of mineral nutrition in conifer ecosystems. Manuscript for *Studia Forestalia Suecica*. In *Understanding and Predicting Tree Growth*. (Sune Linder (ed.)) p. 1-17.
- Kawana, A. and K. Haibara. 1981. Forest fertilization research and practice in the Far East. In *Proc. XVII IUFRO World Congress, Japanese IUFRO Congress Committee, Ibaraki*. p. 50-61.
- Keller, T. 1973. The effect of fertilization on metabolism of forest trees. In *Proc. FAO/IUFRO Intern. Symp. on Forest Fertilization*. Ministry of Agriculture, Paris. p. 55-72.
- Kimmins, J.P., K.A. Scoullar and M.C. Feller. 1980. FORCYTE - A computer simulation approach to evaluating the effect of whole tree harvesting on nutrient budgets and future forest productivity. Unpublished Mimeo. Report, Dept. of Env. 25 pp.
- Kimmins, J.P. 1982. Forcyte Workshop. Petawawa National Forestry Institute, Chalk River, Ontario, July, 1982. Unpublished.
- Konkles, W.W. 1973. Nitrate accumulation in the environment. *Span* 16: 112-114.
- Madgwick, H.A.I., D.S. Jackson and P.J. Knight. 1977. Aboveground dry matter, energy and nutrient contents of trees in an age series of *Pinus radiata* plantations. *N.Z. J. For. Sci.* 7: 445-468.
- Marion, G.M. and A.L. Leaf. 1977. The effect of potassium fertilization and/or irrigation of elemental leaching in a red pine plantation. *Soil Sci. Soc. Amer. Proc.* 41: 432-436.
- Mayhead, G.J. 1976. Forest fertilizing in Great Britain. The Fertilizer Society, London. 18 pp.
- McClellan, G.H. and L.R. Gremillion. 1980. Evaluation of phosphatic raw materials (Chapter 3). In *The Role of Phosphorus in Agriculture*. Amer. Soc. of Agronomy, Madison, Wisconsin.
- McColl, J.G. and D.F. Grigal. 1979. Nutrient losses in leaching and erosion by intensive forest harvesting. In *Impact of Intensive Harvesting on Forest Nutrient Cycling Symp. Proc.*, College of Env. Sci and For., Syracuse, New York. p. 231-248.
- Miller, H.G. 1979. The nutrient budgets of even-aged forests. In *The Ecology of Even-Aged Plantations*. (Ford, E.D. and D.C. Malcolm (eds.)) Institute of Terrestrial Ecology, Cambridge. p. 221-256.

- Miller, R.E. and R.D. Fight. 1979. Fertilizing Douglas-fir forests. USDA For. Serv. Gen. Techn. Rpt. PNW-83. p. 29.
- Morrison, I.R. and N.W. Foster. 1977. Fate of urea fertilizer added to a boreal forest Pinus banksiana Lamb. stand. Soil Sci. Soc. Amer. J. Vol. 41: 441-448.
- Mortvedt, J.J. and H.G. Cunningham. 1971. Production, marketing and use of other secondary and micronutrient fertilizers. In Fertilizer Technology and Use (2nd Ed.) (R.A. Olson et al. (eds.)) Soil Sci. Soc. Amer., Inc., Madison, Wisconsin. p. 413-454.
- Moschler, W.W., G.D. Jones and R.E. Adams. 1970. Effects of loblolly pine on a predominant soil growth, foliar composition and soil nutrients 10 years after establishment. Soil Sci. Soc. Amer. Proc. 34: 683-685.
- Mustanoja, K.J. and A.L. Leaf. 1965. Forest fertilization research 1957-1964. The Botanical Review, 31(2): 151-246.
- National Board of Forestry. 1977. Swedish forest facts about Swedish forestry and wood industries. The National Board of Forestry, Jonkoping. 89 pp.
- Nelson, D.W., L.E. Sommers, D.M. Huber and H.L. Warren. 1977. Conserving energy with nitrification inhibitors. In Agriculture and Energy (William Lockeretz (ed.)) Academic Press, Inc., New York. p. 361-376.
- Otchere-Boateng, J. and T.M. Ballard. 1978. Urea fertilizer effects on dissolved nutrient concentrations in some forest soils. Soil Sci. Soc. Amer. Proc. 42: 502-508.
- Paavilainen, E. 1980. Biomass yields and management of natural coppice stands. IEA/FE Planning Group B - Growth and Production. Report JAB-11. p. 1-52.
- Pang, P.C. and K. McCullough. 1982. Nutrient distribution in forest soil leachates after thinning and fertilizing Douglas-fir forest. Can. J. Soil Sci. 62: 197-208.
- Persson, R. 1974. World forest resources - review of the world's forest resources in the early 1970's. Skogshogskolan Royal College of Forestry, Stockholm. 261 pp.
- Pritchett, W.L. and W.H. Smith. 1975. Forest fertilization in the U.S. southeast. (B. Bernier and C.H. Winget (eds.)) In Forest Soils and Forest Land Management. Proc. 4th N.A. Forest Soil Conference, Laval University, Quebec. p. 467-476.
- Pritchett, W.L. 1979. Properties and management of forest soils. John Wiley & Sons, Toronto, Canada. 500 pp.

- Reed, F.L.C. 1978. Forest management in Canada, Vol. 1. Can. For. Ser. p. 155.
- Rennie, P.J. 1955. The uptake of nutrients by mature forest growth. Plant and Soil VII(1): 49-95.
- Russell, E.W. 1973. Soil conditions and plant growth (10th ed.) Longman Group Ltd., New York. 849 pp.
- Salonen, K. 1980. Environmental effects of forest fertilization in phosphorus in agriculture, No. 77. ISMA Ltd., Paris. p. 23-25.
- Shoulders, E. and A.E. Tiarks. 1980. Fertilizer fate in a 13-year-old slash pine plantation. Soil Sci. Soc. Amer. Proc. 44: 1085-1089.
- Smith, D.M. and E.W. Johnson. 1977. Silviculture: highly energy efficient. J. of For., April 1977: 208-210.
- Sorenson, V.L. 1977. Agricultural policy in energy on environmental dilemma, Proc. (B.A. Stout (ed.)) Michigan State University. p. 104-126.
- Spratt, E.D. and R.M. McIver. 1979. The effect of continual use of phosphate fertilizer and barnyard manure on yield of wheat and the fertility status of a clay chermogen soil. Can. J. Soil Sci. 59: 451-454.
- Stone, E.L. 1979. Nutrient removals by intensive harvest - some research gaps and opportunities. In Impact of Intensive Harvesting on Forest Nutrient Cycling Symp. Proc. College of Env. Sci. and For., Syracuse, New York. p. 366-386.
- Swan, H.S.D. 1960. The mineral nutrition of Canadian pulpwood species. Pulp and Paper Res. Inst. of Can. Techn. Rep. Series 168. p. 1-66.
- Swan, H.S.D. 1966. Studies of the mineral nutrition of Canadian pulpwood species. Pulp and Paper Res. Inst. of Can. Techn. Rep. Series 464. p. 1-11.
- Switzer, G.L. and L.E. Nelson. 1973. Maintenance of productivity under short rotation. In Proc. FAO/IUFRO Intern. Symp. on Forest Fertilization. Ministry of Agriculture, Paris. p. 365-389.
- Tamm, C.O. 1964. Determination of nutrient requirements of forest stands. Intern. Review of For. Res. 1: 115-170.
- Tamm, C.O. 1968. The evolution of forest fertilization in European silviculture. In Forest Fertilization - Theory and Practice. Tennessee Valley Authority, Muscle Shoals, Alabama. p. 242-247.

- Tarrant, R.F. and R.R. Silen. 1966. Growth and nutrient uptake of irrigated young Ponderosa pine after fertilizer treatments. Soil Sci. Soc. Amer. Proc. 30: 796-799.
- Tarrant, R.F. 1978. Attitudes toward red alder in the Douglas-fir region. In Utilization and Management of Alder. USDA For. Serv. Gen. Tech. Rep. PNW-70. p. 1-7.
- Uusitalo, M. 1979. Yearbook of forest statistics 1977-78. Folia. For. 375. Official Statistics of Finland. SVIIA: 10. p. 197.
- Van Cleve, K. and T.A. Moore. 1978. Cumulative effects of nitrogen, phosphorus and potassium fertilizer additions on soil respirations, pH and organic matter content: Soil Sci. Soc. Amer. J. 42: 121-124.
- Van Hook, R.I., D.W. Johnson, D.C. West and L.K. Man. 1982. Environmental effects of harvesting forests for energy. For. Ecol. Manage. 4: 79-94.
- Van Lear, D.H. 1980. Effects of nitrogen, phosphorus and lime on the forest floor and growth of pole-size loblolly pine. Soil Sci. Soc. Amer. J. 44: 838-841.
- Waring, H.D. 1973. Early fertilization for maximum production. In Proc. FAO/IUPRO Intern. Symp. on Forest Fertilization. Ministry of Agriculture, Paris. p. 215-241.
- Ward, W.W. and T.W. Bowersox. 1970. Upland oak response to fertilization with nitrogen, phosphorus and calcium. For. Sci. 16: 113-120.
- Weetman, G.F., M.R. Roberge and C.H. Meng. 1980. Black spruce: 15-year growth and microbiological responses to thinning and fertilization. Can. J. For. Res. 10: 502-509.
- Wells, C.G. and J.R. Jorgensen. 1979. Effect of intensive harvesting on nutrient supply and sustained productivity. In Impact of Intensive Harvesting on Forest Nutrient Cycling Symp., College of Env. Sci. and For., Syracuse, New York. p. 212-230.
- Wiklander, G. 1977. Effects of forest fertilization on soil and water - Sv. Skogavardsfora.tidska 75(2-3), 179-187. (Swedish with English Abstract).
- Wilde, S.A. 1961. Comments on tree nutrition and use of fertilizers in forestry practice. J. of For. 59(5): 346-348.
- Wittwer, R.F., M.J. Immel and F.R. Ellingsworth. 1980. Nutrient uptake in fertilized plantations of American sycamore. Soil Sci. Soc. Amer. Proc. 44: 606-610.

APPENDIX I

Production, Consumption and Movement of Nitrogenous Fertilizers in Selected Countries During 1979-80

Country	Production	Consumption metric tonnes	Imports	Exports
Norway	452,400	113,200	-	329,100
Belgium-Lux.	756,100	15,600	-	806,000
Finland	259,504	196,241	794	44,485
Ireland	102,200	247,500	143,500	22,600
Sweden	171,355	256,257	119,800	4,671
Canada	1,675,100	807,400	136,200	919,900
U.S.A.	11,180,000	10,341,404	2,348,000	2,396,000
U.K.	1,316,000	1,314,000	189,000	92,000
Denmark	130,038	393,900	265,689	-
New Zealand	-	25,000	25,000	-
Japan	1,493,000	777,000	44,000	773,000
U.S.S.R.	9,074,000	7,467,000	15,300	813,200
China	9,095,200	10,551,500	1,473,400	22,500
India	2,224,300	3,451,615	1,295,300	-

(from: FAO, 1981)

APPENDIX II

Production, Consumption and Movement of Phosphate Fertilizers in Selected Countries During 1979-80

Country	Production	Consumption metric tonnes	Imports	Exports
Norway	146,300	65,900	-	80,700
Belgium-Lux.	618,000	103,500	53,000	533,000
Finland	185,699	150,002	382	32,642
Ireland	41,600	155,700	116,200	4,100
Sweden	128,524	129,225	20,571	7,632
Canada	685,200	626,000	171,700	212,100
U.S.A.	9,083,000	4,890,703	220,000	3,561,000
U.K.	472,000	460,000	93,200	57,300
Denmark	115,345	133,181	45,649	29,173
New Zealand	410,500	416,300	18,600	2,000
Japan	743,700	831,000	96,800	-
U.S.S.R.	5,930,000	5,480,000	14,200	220,200
China	1,869,900	1,952,600	75,600	2,300
India	779,100	1,014,900	237,100	-

(from: FAO, 1981)

APPENDIX III

Production, Consumption and Movement of Potash Fertilizers in
Selected Countries During 1979-80

Country	Production	Consumption metric tonnes	Imports	Exports
Norway	-	87,400	178,900	-
Belgium-Lux.	-	158,000	355,000	-
Finland	-	143,556	191,275	-
Ireland	-	189,100	222,400	-
Sweden	-	121,686	134,637	-
Canada	7,063,000	383,900	26,900	6,432,200
U.S.A.	2,097,000	5,589,337	4,901,000	951,000
U.K.	276,000	461,000	423,000	134,600
Denmark	-	170,676	190,000	-
New Zealand	-	107,700	107,700	-
Japan	-	736,000	767,000	-
U.S.S.R.	6,635,000	4,411,000	2,281,001	1,985,700
China	16,000	295,800	276,300	-
India	-	545,470	473,200	-

(from: FAO, 1981)

APPENDIX IV

Major Phosphate Reserves and Resources (metric tons, at least 30% P_2O_5)

Location	Reserves	Resources
<u>Marine Phosphorite</u>		
Algeria	500 x 10 ⁶	600 x 10 ⁶
Morocco	5,000 x 10 ⁶	35,000 x 10 ⁶
Tunisia	500 x 10 ⁶	800 x 10 ⁶
Western Sahara	1,600 x 10 ⁶	15,000 x 10 ⁶
Egypt	800 x 10 ⁶	2,000 x 10 ⁶
U.S.S.R.	1,450 x 10 ⁶	2,950 x 10 ⁶
Australia	500 x 10 ⁶	1,500 x 10 ⁶
U.S.A.	7,600 x 10 ⁶	13,000 x 10 ⁶
Brazil	200 x 10 ⁶	500 x 10 ⁶
<u>Apatite (Igneous Origin)</u>		
U.S.S.R.	400 x 10 ⁶	400 x 10 ⁶
South Africa	100 x 10 ⁶	1,300 x 10 ⁶
Brazil	237 x 10 ⁶	775 x 10 ⁶
Finland	50 x 10 ⁶	100 x 10 ⁶
<u>Guano Derivatives</u>		
Nauru Island	50 x 10 ⁶	-
Christmas Island	100 x 10 ⁶	70 x 10 ⁶
<u>Guano</u>		
Chile	Few tens of thousands	1,000
Philippines	50,000	-
Indonesia	50,000	-

(from: Cathcart, 1980)

POOR

QUALITY

ORIGINAL